JPL PUBLICATION 79-114

Roadside Tree/Pole Crash Barrier Field Tests

A. H. Wilson

(NASA-CR-162788) ROADSIDE TREE/POLE CRASH BARRIER FIELDS TESTS (Jet Propulsion Lab.) 52 p HC A04/MF A01 CSCL 13F

N80-17917

Unclas

G3/85 47257

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100.

ABSTRACT

A series of tests was carried out by the Jet Propulsion Laboratory (JPL) under the sponsorship of NASA to evaluate the performance of a unique crash barrier designed to protect the occupants of an automobile from serious injury. The JPL barrier design is a configuration of empty aluminum beverage cans contained in a tear-resistant bag which, in turn, is encased in a collapsible container made of plywood and steel. Tests were conducted with a driven vehicle impacting the barrier. The basic requirements of NCHRP Report 153 were followed except that speeds of 30 mph rather than 60 mph were used. Accelerometer readings on the driver's helmet showed that he was never subjected to dangerous decelerations, and in no case did the driver experience more than temporary discomfort. Also, all of the requirements of the cited report were met.

An extrapolation of data indicated that the JPL barrier installed in front of a tree or telephone pole along a roadside would also have met the requirements at a speed of 40 mph.

ACKNOWLEDGMENT

The author gratefully acknowledges the invaluable assistance of the Pennsylvania Department of Transportation, California Department of Transportation, and to Paul O'Shea of California Auto Research (a commercial test firm).

Special thanks are extended to Ruth Lizack of SRI International for her helpful comments and to the JPL technicians who contributed to the tests. Thanks are also extended to Bain Dayman of JPL for his work on the program and particularly for his comments on this report.

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SECTION I

INTRODUCTION

A series of vehicle crash tests was performed by the Jet Propulsion Laboratory (JPL), under the sponsorship of the NASA Office of Technology Utilization, to evaluate and demonstrate the performance and effectiveness of the JPL barrier design. The JPL barrier design is a configuration of empty aluminum beverage cans contained in a tear-resistant bag which, in turn, is encased in a collapsible container made of plywood and steel.

A. PROBLEM

An evaluation of data from the Federal Coordination Program Project (Reference 1) showed that in the category of non-superhighway accidents, 200,000 involved trees, 4,000 of which caused fatalities, and 240,000 involved poles, 25,000 of which caused fatalities. The data showed that crashes at automobile speeds of 30-35 mph are common, and discussions with highway engineers have confirmed the problem's importance. Since there is a definite need for protection against crashes into roadside trees and poles at speeds as low as 30 mph, a natural step in the development of the JPL concept was to perform tests at automobile crash speeds at less than the 55-60 mph for which the present gore barriers are designed. The Appendix contains additional pertinent accident data.

B. BACKGROUND

Several of the safe and effective crash barrier systems that have been developed for use on highways provide impact protection up to

60 mph. These are generally placed in front of rigid highway obstacles such as roadway gores (off-ramp wedges) and abutments. One such system was investigated by JPL in 1976 and 1977 (Reference 2) under a program sponsored by NASA. The feasibility of using empty aluminum beverage cans in a crash barrier was demonstrated by JPL during that investigation for speeds up to 30 mph. The crushing-force history is very orderly and of a nature that is expected to be more benign to the occupants of vehicles than the gore barriers now in use. It should be noted that field tests at 30 mph can be more readily carried out than similar tests at the higher speeds.

C. GOALS

Because available data are based on a great variation in tree and pole locations and dimensions, it was decided to contact several highway departments to set reasonable standards for the tests. An 11-in. diameter pole located with its center line 24 in. from the paved roadway was established as a reasonable "standard" tree (pole) to protect with a barrier. Also, tests at 30 mph would be appropriate since crashes at speeds of 30-35 mph are common, as stated above.

Design goals were:

(1) A total installation cost of less than $500.

(2) A barrier that would meet the requirements of NCHRP Report 153 (Reference 3) except that the impact speed would be 30-35 mph.

(3) A device that would be non-proprietary.

SECTION II

CRASH BARRIER DESIGN

AND

INSTALLATION REQUIREMENTS

A. SUMMARY OF PREVIOUS WORK

1. Laboratory Tests

Static tests carried out at JPL in 1976 showed that compressing one 12-oz aluminum beverage can will dissipate 28 ft-lb of energy at 72% can compression. These tests were essentially static tests in that compression took place over a period of several minutes. When similar tests were carried out on a large number of cans that formed a module, the energy absorption per can remained about the same. In all of these tests the cans were loaded axially.

Vehicular crash tests indicated that the dynamic energy dissipation per can was substantially higher than the static (about two or three times). To verify this in laboratory tests, weights were dropped from various heights, axially, on empty aluminum beverage cans. Typically, a single can absorbed in excess of 60 ft-lb of energy at about 80% compression. However, when a 300-lb weight was dropped a distance of 7 1/2 ft on a container containing 48 axially-oriented cans, the energy absorbed per can was 36 ft-lb at about 80% compression. This value was somewhat higher than the static test but substantially less than that of the dynamic test on the single can or the actual crash test. The reasons for the differences in the results of the various dynamic tests were not clear.

In an attempt to better understand the reasons for the increase in energy absorption of dynamic static compression, calculations were made on the effect of internal pressure in the can on the buckling loads. Results are tabulated in Table 2-1. The difference may be explained by assuming that no air leaks through the tab opening or elsewhere during impact. When the can is compressed to 80% of its original length using an isentropic compression ($n = \gamma = 1.4$), the work to compress the air is calculated to be 1.8 times the work to crush the can in a slow manner. Actually, each can had a hole where the tab had been removed. This hole is an effective vent for "static" tests. However, during rapid crush it would act as a restriction to the escaping air even if not blocked off by an adjacent can. Hence it seems reasonable that there could be an internal pressure of some amount. The amount of this buildup would govern the energy absorption performance of the can.

Table 2-1. Internal Pressure vs Allowable Axial Load

Internal Pressure (psi)	Allowable Axial Load (lb)
0	215
5	443
10	520
20	607

2. Field Tests

a. Vehicle. In a previous series of tests performed by JPL, both at JPL and at the Caltrans Sacramento facility, the test vehicle was pushed by a pick-up truck into the JPL crash barriers. To do this it was necessary to accelerate the truck continuously to maintain contact with the test vehicle. Before impact the pusher would decelerate, and, after contact with the test vehicle was lost, the pusher could safely change its course. It was found that controlling the test vehicle direction accurately by pushing in this manner was easy at speeds up to 25 mph, but it became difficult at 30 mph and not feasible at higher speeds.

b. Barrier. In early tests, when all rows of cans were oriented axially in the crash direction, it was found that deflections were less than expected and that g loads were high. Placing randomly-oriented cans in the front part of the barrier bag resulted in greater deflection, much more uniform deceleration, and lower g loads.

B. RECENT CHANGES

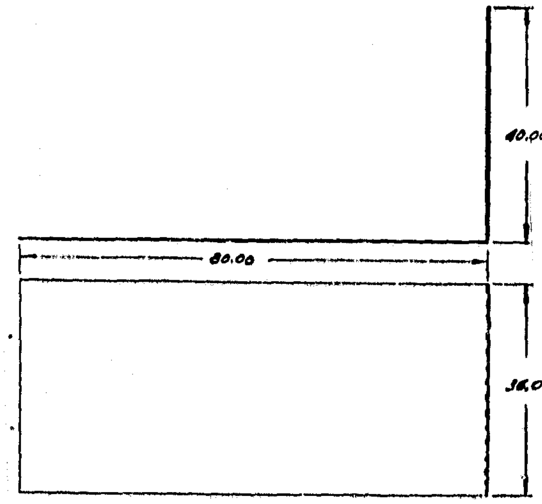
Because empty 12-oz beverage cans weigh only about 1/20 lb each, the modular crash cushion is quite light, is easily handled, and can be arranged in a wide variety of configurations. The crash barrier design used for the current field tests was based on and was influenced by the results of previous work. The JPL concept is the primary element of this test barrier as shown in JPL Drawing 10091568 (Figure 2-1). The entire barrier is fabricated from readily-available materials and is easy to install. It is approximately 6 ft long, 3 ft high, and 3-1/2 ft wide. On impact, the side panels slide past the backstop as the beverage cans collapse. The two 4 in. x 6 in. wood posts prevent lateral motion of the barrier and also prevent it from rotating. The 11-in. diameter poles serve as a backstop support, and also help to prevent rotation to the side. The fabric bag contains the cans and prevents them from spilling out of the container on impact. It is made of a flame-retardant weather-resistant fabric.

C. MODIFICATION TO ACCOMMODATE TREES AND POLES

To control the stiffness of the JPL barrier effectively, a brief investigation was made for randomly-oriented empty aluminum beverage cans (the cans are simply tossed into a container). Several dynamic tests (dropping weights) (see Paragraph A.1.) were carried out to determine the energy absorption capability. The results showed that the energy absorption of a given volume of randomly-oriented aluminum beverage cans under dynamic crush is about the same as that of the same volume of cans under static crush. It should be noted that the number of cans in the random orientation is about 85% of the number of uniformly-oriented cans in the same volume.

In previous tests, in which 1/4-in. mesh metal screening (hardware cloth) was used as the can-containing vessel, a large number of cans scattered on the roadway after impact. The use of a fabric bag effectively prevented this scattering.

In establishing test goals (see Section I, Paragraph C), the assumption that the pole center-line would be placed 24 in. from the road edge precluded the use of a longer barrier, because such a barrier itself might be a hazard if it extended too close to the roadway.



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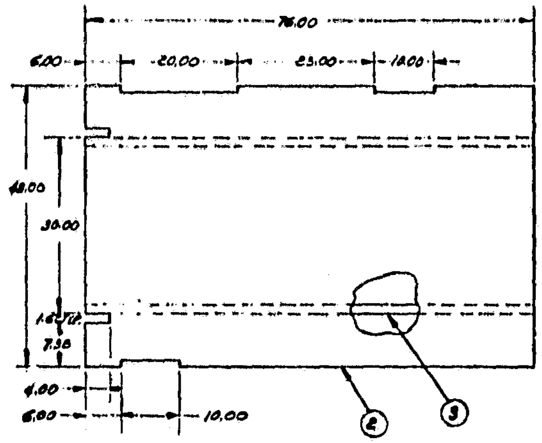

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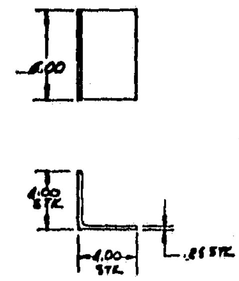

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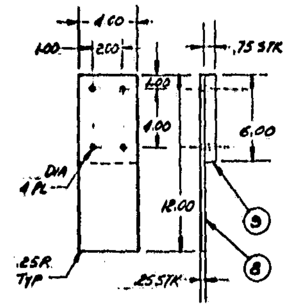

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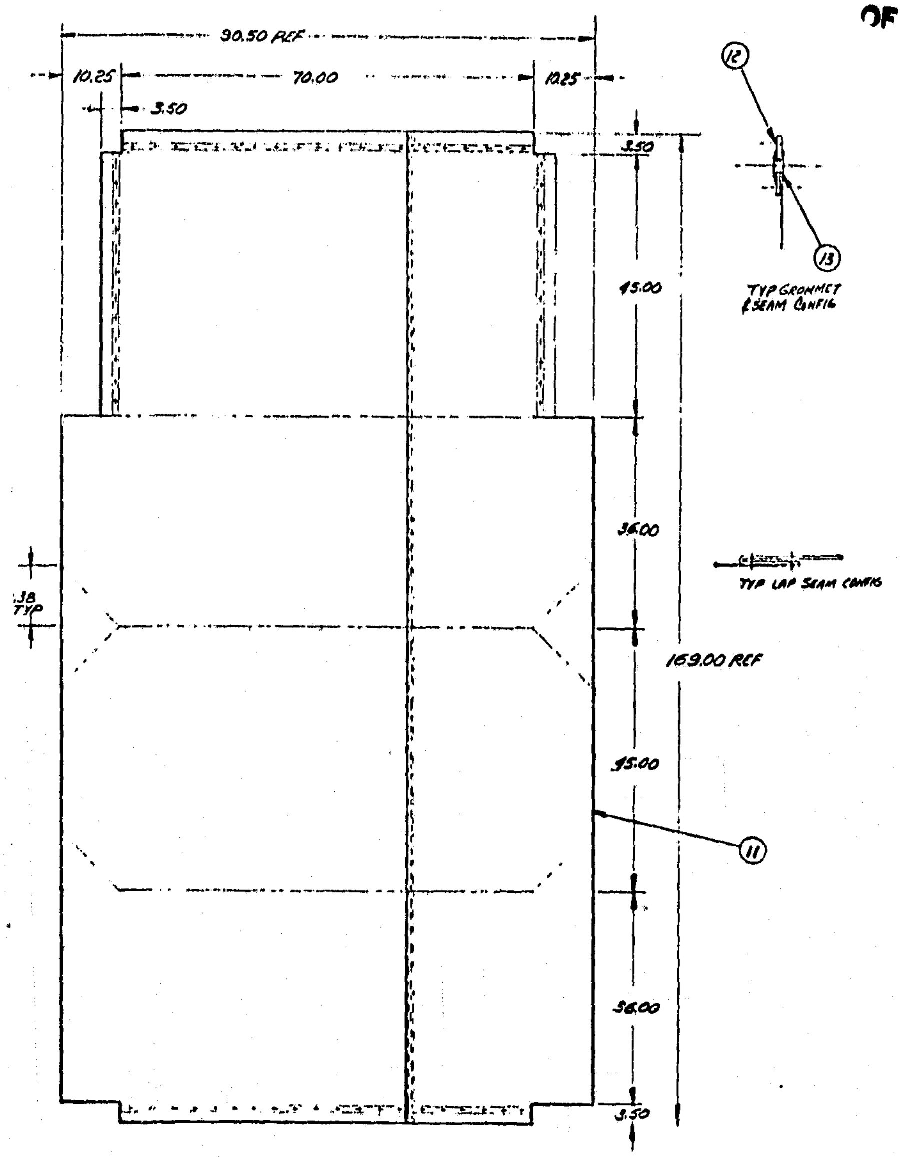

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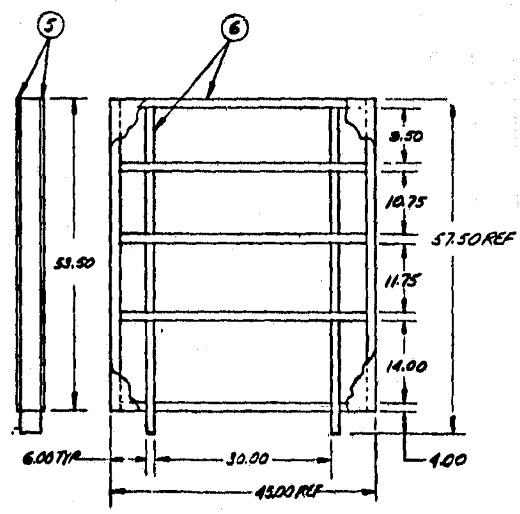

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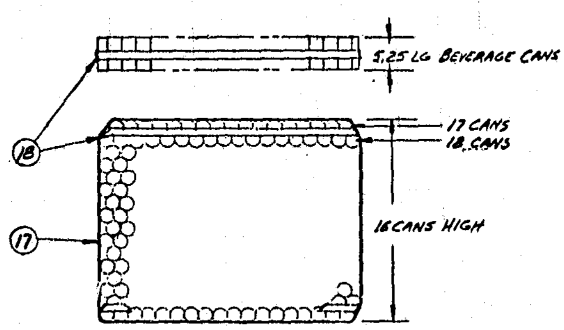

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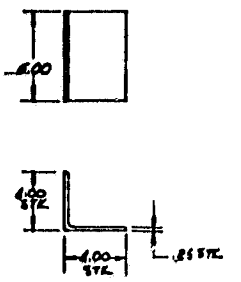

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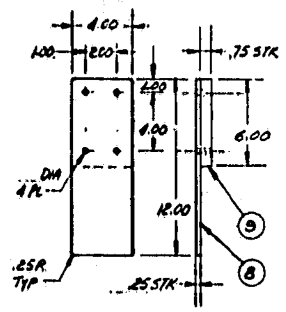

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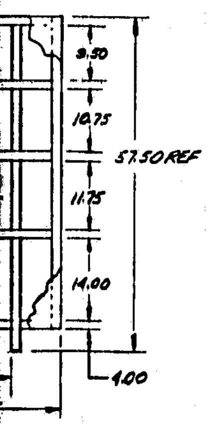

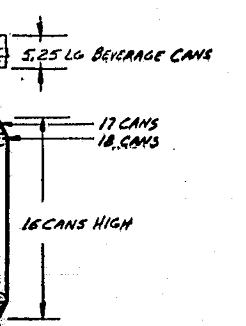

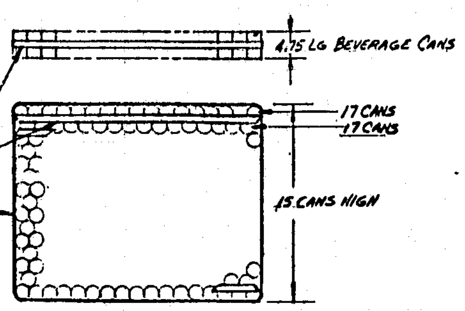

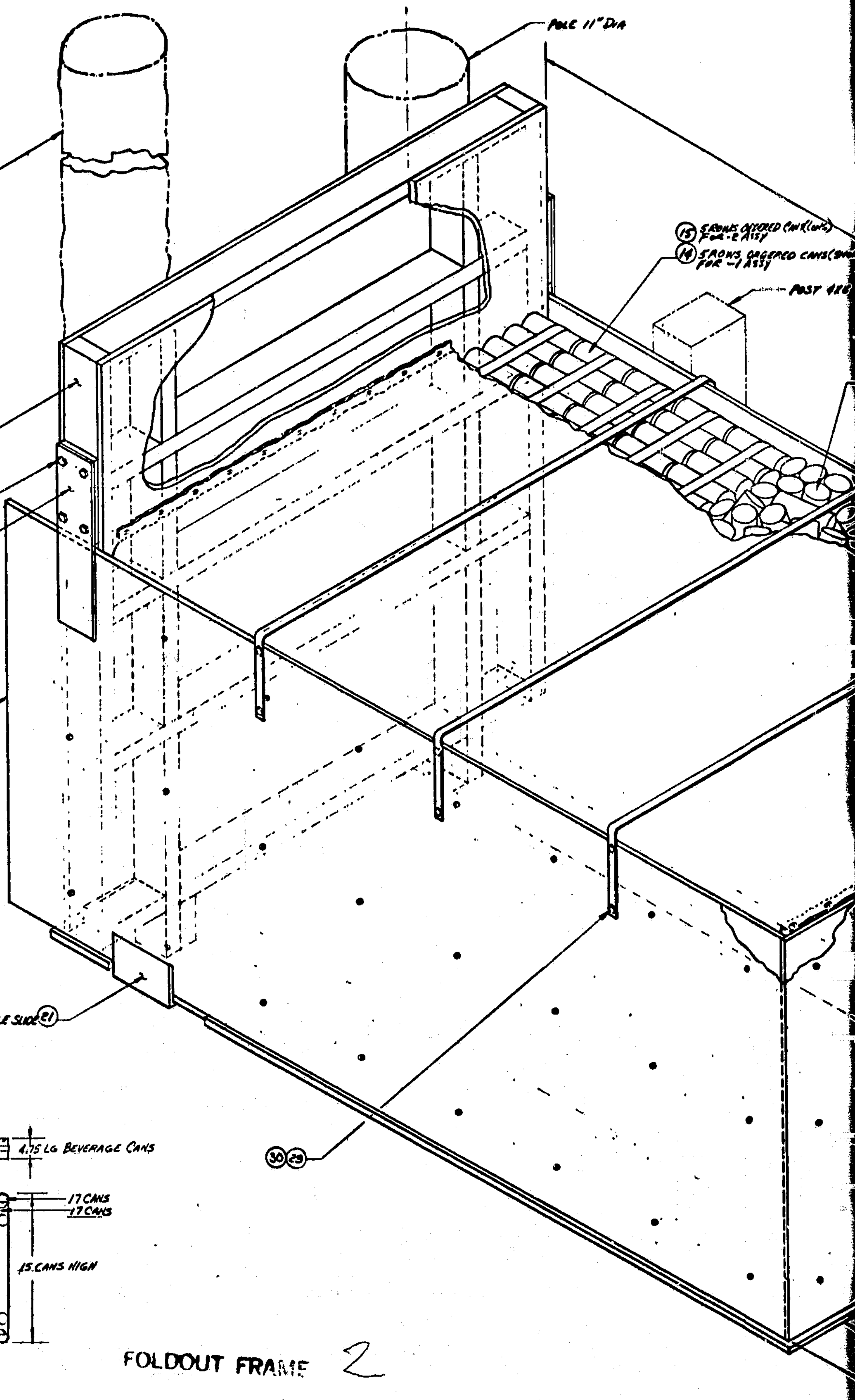

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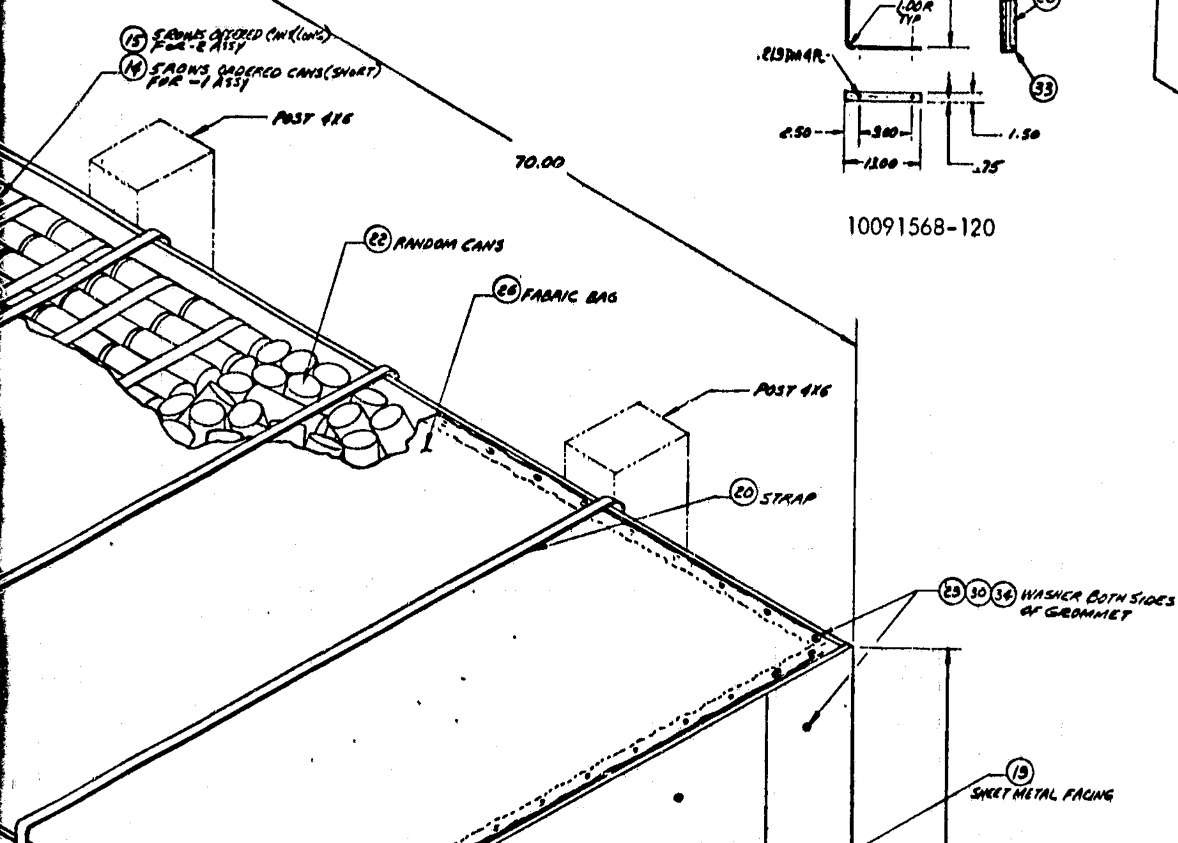

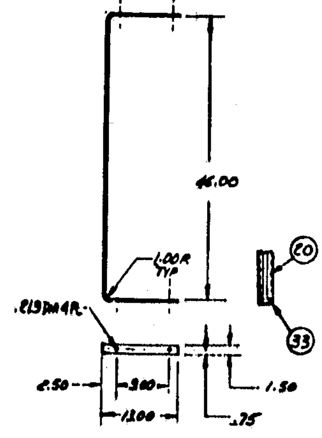

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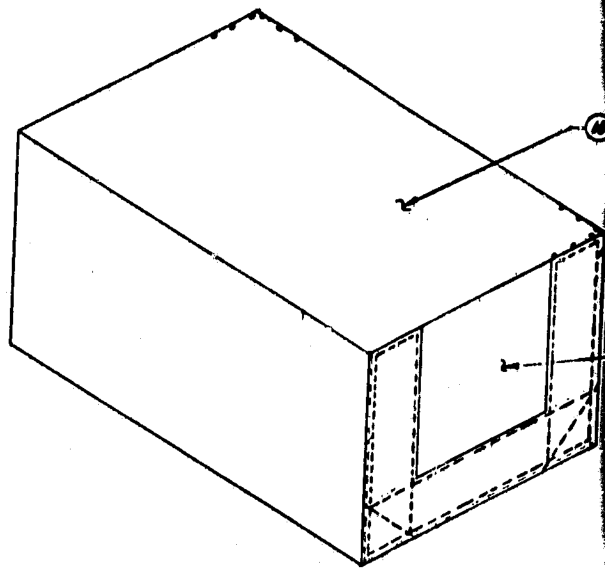

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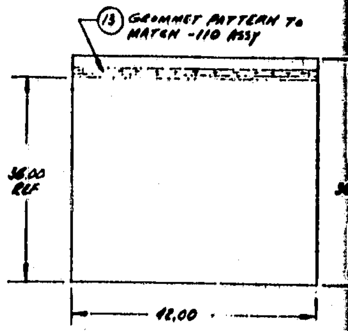

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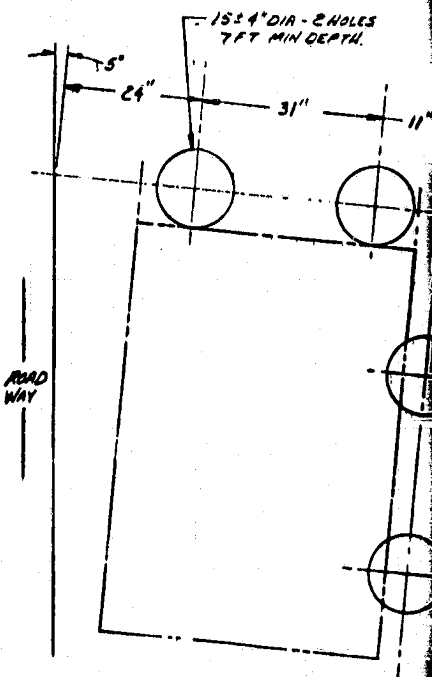

POST HOLE CONFIGURATION

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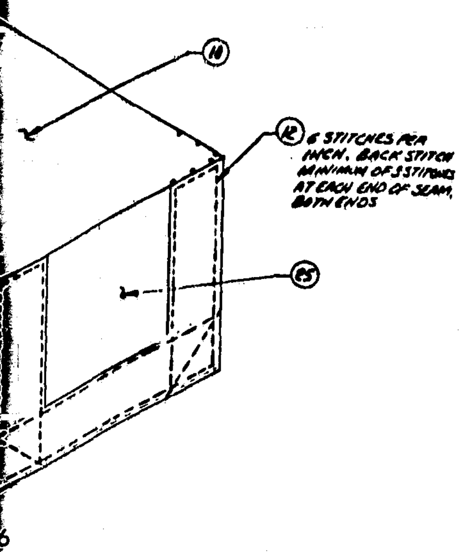

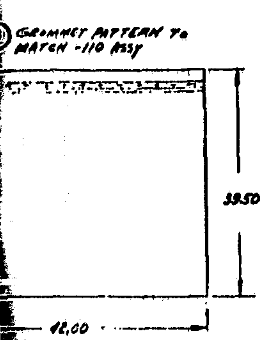

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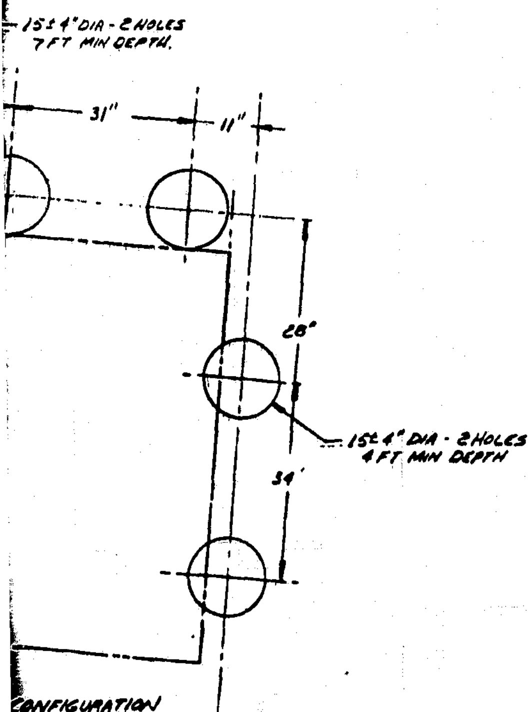

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								QTY REQD						
								AR	AR	34				WASHER
								AR	AR	33				TAPE 2"
								8	8	32				NUT
								8	8	31				SCREW,
								AR	AR	30				NUT
								AR	AR	29				SCREW,
								~~AR~~	~~AR~~	~~28~~				~~CLIPS~~
								~~AR~~	~~AR~~	~~27~~				~~CABLE, T~~
X								1	1	26				BAG
2	X									25				BAG, END
								2	2	24				SIDE PAN
								1	1	23				FRONT PA
								AR	AR	22				CANS, RA
								2	2	21				ANGLE, S
								3	3	20				STRAP
								2	2	19				SHEET ME
		AR	AR							18				TAPE, 1"
		280								17				CAN, LON
			255							16				CAN, SHO
		X						5		15				ORDERED
			X						5	14				ORDERED
	AR			AR						13				GROMMET
AR	AR			AR						12				THREAD
2	1			1						11				FABRIC
1				X						10				BAG, FLAT
					1					9				SPACER
					1					8				PLATE
					X			2	2	7				BRACKET,
						AR				6			-106	2 X 4
						2				5			-105	PLYWOOD
						X		1	1	4			-104	BACK STO
							2			3			-103	2 X 4
							1			2			-102	PLYWOOD
							X	1	1	1			-101	BASE

FOLDOUT FRAME 4

REF DES	CODE IDENT NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	SPECIFICATION	MATERIAL OR NOTE	ZONE
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			TAPE 2" WIDE			
			NUT		1/4	
			SCREW, MACHINE		1/4	
			NUT		#10-32	
			SCREW, MACHINE		#10-32 X 3/4 LG	
			~~CLIPS~~			
			~~CABLE, TIE DOWN~~			
			BAG			
			BAG, END PANEL			
			SIDE PANEL		3/8 X 35 X 80	
			FRONT PANEL		3/8 X 45 X 36	
			CANS, RANDOM			
			ANGLE, SLIDE			
			STRAP	CONSISTS OF ITEM 20 & 33	GALVANIZED 18 GAGE	
			SHEET METAL FACING		GALVANIZED 18 GAGE	
			TAPE, 1" WIDE			
			CAN, LONG		2 1/2 OD X 5 1/4 LG	
			CAN, SHORT		2 1/2 OD X 4.75 LG	
			ORDERED CANS, LONG			
			ORDERED CANS, SHORT			
			GROMMET		00	
			THREAD		STAR ULTRA-D NATURAL #12 DACRON	
			FABRIC		PVC-1800 LAMINATED NYLON FABRIC	
			BAG, FLAT			
			SPACER		3/4 X 4 X 6	
			PLATE		1/4 X 4 X 12 AL-2024-73	
			BRACKET, SLIDE			
		-106	2 X 4		370" TOTAL LENGTH	
		-105	PLYWOOD		1/2 X 45 X 57 1/2	
		-104	BACK STOP		1/2 X 45 X 53 1/2	
		-103	2 X 4		76 LONG	
		-102	PLYWOOD		1/2 X 48 X 76	
		-101	BASE			

Figure 2-1. Crash Barrier
(From JPL Drawing No. 10091568)

SECTION III

TEST PROGRAM

A. OBJECTIVE

The purpose of the test program described herein was to evaluate the performance of the JPL barrier concept by a series of tests that were representative of actual crashes. The barrier was therefore subjected to the conditions of NCHRP Report 153, except as noted, to determine whether it met its requirement. The barriers were designed to protect the occupants of an automobile from serious injury at speeds of 30-35 mph should their car be directed at a tree or telephone pole protected by the barrier. Also, the tests were to provide subjective information from the driver of the vehicle pertaining to aspects of the crash and the physical effect of the impact upon himself.

B. APPROACH

It was decided to use instrumented vehicles driven by a professional driver for the following reasons:

(1) Confidence had been firmly established in the JPL concept during the pushed-car tests.

(2) Much better control of the impact of the car with the crash barrier would result than by pushing.

(3) It would be valuable to have first-hand experience (from an occupant of the crashed vehicle).

(4) Tests conducted with a driver were determined to be actually less expensive than with towed or pushed cars.

Discussions with Caltrans (California Department of Transportation) engineers led, in turn, to discussions with California Auto Research (CAR), an organization that had satisfactorily performed tests for Caltrans. An agreement was reached with CAR to perform the JPL test procedures and to use the Orange County Raceway facilities in Irvine, California, for the tests. It was decided that CAR would provide the driver, the test cars, and the labor required to install the barriers, which included digging the holes for support posts. JPL would prepare and supervise the test program, and provide the barrier, materials, technicians, and equipment for photographic and accelerometer measurements.

C. PREPARATION FOR TESTS

1. Car

Cars were prepared for crash tests in two weight categories, 2250 and 4500 lb. Each car was weighed, and ballast was added, if required, to meet the requirements of Reference 3. The speedometer in each car was checked in the 30 mph range. The cars were painted yellow in order to enhance motion picture data.

For safety, the door on the driver's side of the car was removed and two steel pipes were welded in its place. This served as a sure escape area and also enabled a high-speed camera to photograph the driver's reaction better during impact. In addition, steel tubes were placed between the hood and the windshield so that if the hood came off it would slide up the tubes rather than penetrate the windshield.

2. Driver

To provide safety for the driver, he was provided with a helmet, seat belt, and shoulder harness. One of the accelerometers (see Paragraph 3.a.) was installed on his helmet to monitor head motion.

3. Instrumentation

a. Accelerometers. Three accelerometers were used within each test vehicle; two were installed to measure axial acceleration on the car frame and a third was fastened to the driver's helmet. The accelerometers used were Donner Servo-accelerometers, No. 4130. Each accelerometer output went through signal conditioning equipment and was recorded both on a direct-write Brush 680 recorder and on an Ampex CP100 magnetic recorder.

Basic accelerometer calibration was performed both at JPL using an Unholtz-Dickie 350B vibration system calibration and at the test site by a turn-over calibration to verify +1 g and -1 g accelerations.

b. High-speed Cameras. Two high-speed 16 mm motion picture cameras having a nominal rate of 500 frames/sec were used to photograph the impact. The first camera was located with its axis perpendicular to the side of the barrier. The second camera photographed the impact from behind the car as it impacted. Its axis was almost parallel to the barrier axis. The first camera recorded a pulse on the film each 1/120 sec. This pulse, together with a grid near the impact point, was used to establish the impact speed. These cameras were used to observe the trajectory and motion of both the car and the driver during impact with the barriers.

4. Barrier

In the 15 mph tests (the first tests run with a driver) as described in Paragraph D below, conventional telephone pole installations were used. They were inserted vertically only about 3 ft into the ground, and slow speed tests showed this to be inadequate. The pole was then inserted about 6 ft into the ground, but at 30 mph it was found that the 11-in. diameter telephone poles would often shear or split. Consequently, in the final tests, steel poles with fins (for strength and stabilization) were used to simulate the telephone poles. These poles, inserted vertically 6 ft into the ground, would sustain the three or four impacts during a test period; i.e., remain upright and unbent.

The crash barrier installation, as defined in Figure 2-1, was then completed.

D. DESCRIPTION OF TESTS

The tests were carried out as planned on a portion of the 3000-ft long drag strip at the Orange County Raceway located in Irvine, California. Initial impact tests were made at 15 mph to check out the test procedures, the instrumentation, and especially the effects upon the driver. Modifications in the instrumentation, in the barrier backstop, and in the method of retaining cans in the barrier had all resulted from early test findings (see Section II).

Seventeen (17) tests were made during the period of August 1978 - July 1979. The instrumented vehicles were driven by a professional driver, Mr. Paul O'Shea of CAR. Tests that were carried out in this series are listed in Table 4-1. Note that several of these tests were carried out on barriers consisting of empty 55-gal chemical drums.

Different configurations of these drums were investigated for purposes of performance comparison with that of the JPL barrier design.

SECTION IV

RESULTS

Test results indicated that the JPL barrier met all of the requirements that were imposed upon it and, through the subjective comments of the driver, that the shock was less than that of impacting 55-gal drums. Instrumented test data also showed that both peak and overall accelerations were higher for 55-gal drum barriers than for JPL barriers.

A test summary that shows the configuration of the test barriers for each of the 17 final tests is presented in Table 4-1 and Figure 4-1. The CAR personnel were most cooperative in all phases of the test program, and they performed very well.

A. BASIC DATA

1. Car

Three accelerometer traces for each test run were obtained. Examples appear in Figures 4-2, 4-3, and 4-4. From these data the average accelerations were computed and are listed in Table 4-2.

In all tests for each car weight using the JPL crash barrier, the duration of impact was greater than 300 ms; hence the average acceleration for each test was less than 5 g (refer to Table 4-2). The peak decelerations were greater, but for much shorter periods of time. The average decelerations for shorter durations are also shown in Table 4-2. Note that the peak acceleration recorded for the car is only around 13 g with the maximum average over 50 ms being only 9 g.

Table 4-1. Test Summary

Test	Configuration	Car Weight (lb)	Impact Speed (mph)	Off-axis Angle* (deg)	Offset**	Notes
1	Panelled enclosure; oriented cans	4500	15	15	None	Earth moved; pole tilted (pole dia 11 in.)
2	Same as 1	4500	15	15	None	Same as 1
3	Similar to 1	4500	15	15	3 ft	Same as 1
4	2 - 55-gal drums	4500	15	15	None	Same as 1; front of car captured by barrel
5	3 - 55-gal drums	4500	15	15	None	Same as 1
6	Same as 1	4500	30	20	None	Pole sheared; pole imbedded in ground 6 ft
7	Same as 1	4500	30	20	None	Same as 6
8	3 rows of 55-gal drums; 2 drums per row; oriented cans in rows 1 and 3, empty drums in row 2	2250	30	0	1 ft	Same as 6
9	Same as 1	4500	30	0	1 ft	Steel pole with welded fins; no pole motion
10	Same as 1	4500	30	0	1 ft	Same as 9
11	Panelled enclosure, random cans	2250	30	0	1 ft	Same as 9; cans scattered
12	Similar to 8; all drums empty; no hole in top of 1st row	2250	30	0	1 ft	Same as 9

*Off-axis angle is the angle between the vehicle center line and the barrier center line measured in degrees (see Figure 4-1)
**Offset is the lateral distance between the vehicle center line and the barrier center line measured in feet (see Figure 4-1)

Table 4-1. Test Summary (Continuation)

Test	Configuration	Car Weight (lb)	Impact Speed (mph)	Off-axis Angle* (deg)	Offset**	Notes
13	Panelled enclosure; combination of oriented and random cans	4500	30	0	2 ft	Same as 9; low g
14	Same as 13	2250	30	0	None	Same as 13
15	Same as 13	4500	30	0	None	Same as 13
16	Same as 13	4500	30	0	None	Same as 13
17	Same as 13	4500	30	15	2 ft	Same as 13

*Off-axis angle is the angle between the vehicle center line and the barrier center line measured in degrees (see Figure 4-1)
**Offset is the lateral distance between the vehicle center line and the barrier center line measured in feet (see Figure 4-1)

It should be noted that most cars were used for two crashes, although some were used three times. This was possible because the damage incurred was not critical to the car operation. However, each crash did use up some of the car's inherent impact absorption capability, hence making each succeeding test with the same car a more severe demonstration of the JPL barrier capability.

Selected photos from the motion picture data of Runs 13 through 17 were analyzed. Acceleration data obtained from these pictures match the accelerometer data except that the peaks are not as pronounced. This is due to the averaging technique used in the photo data analysis method.

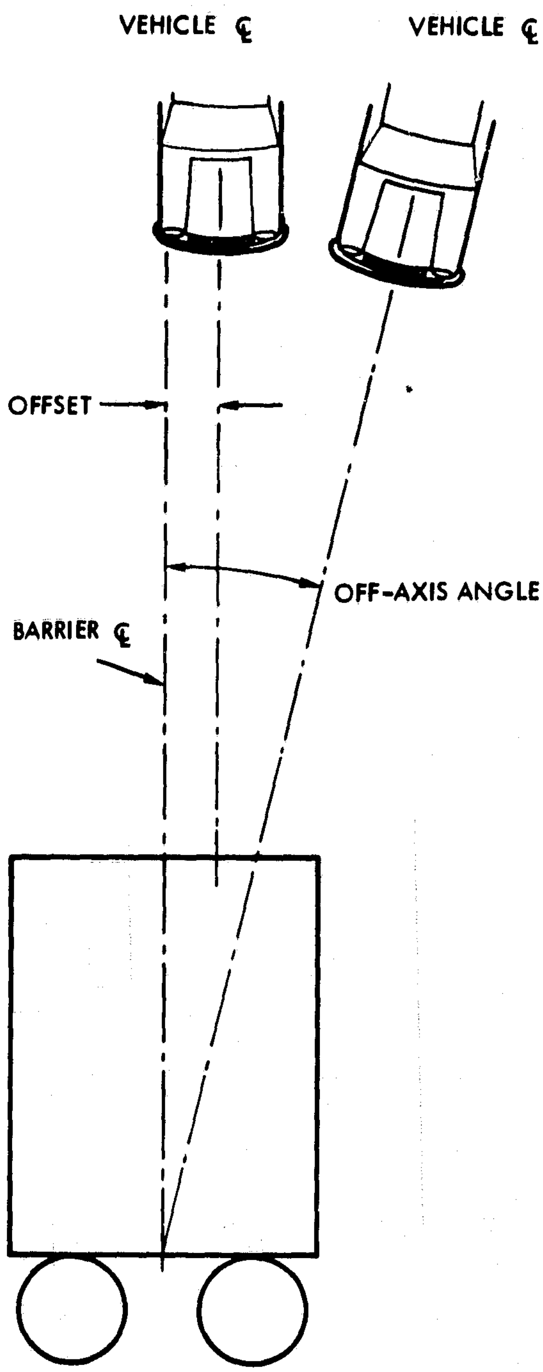

Figure 4-1. Off-axis Angle and Offset Definitions

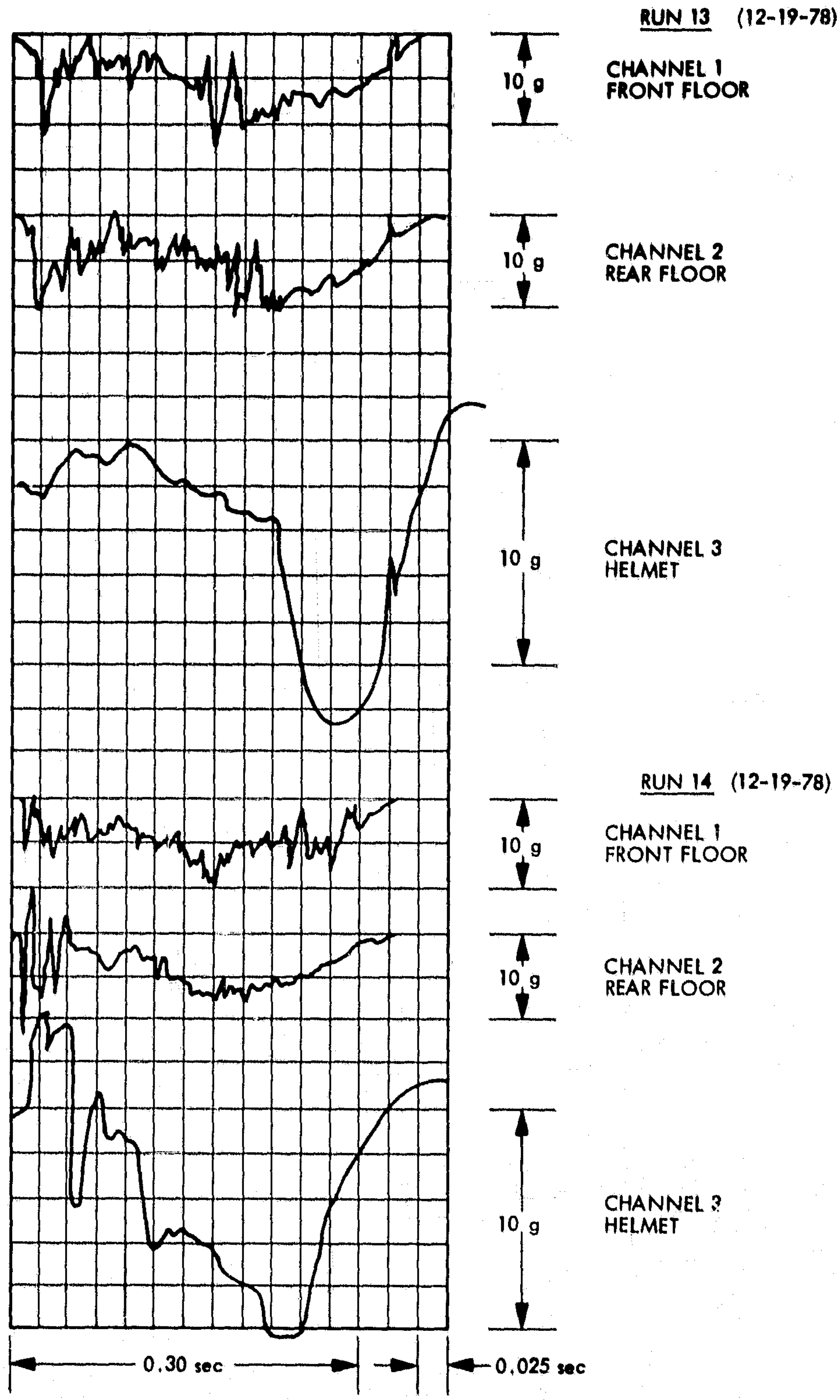

Figure 4-2. Accelerometer Traces; Run 13 and Run 14

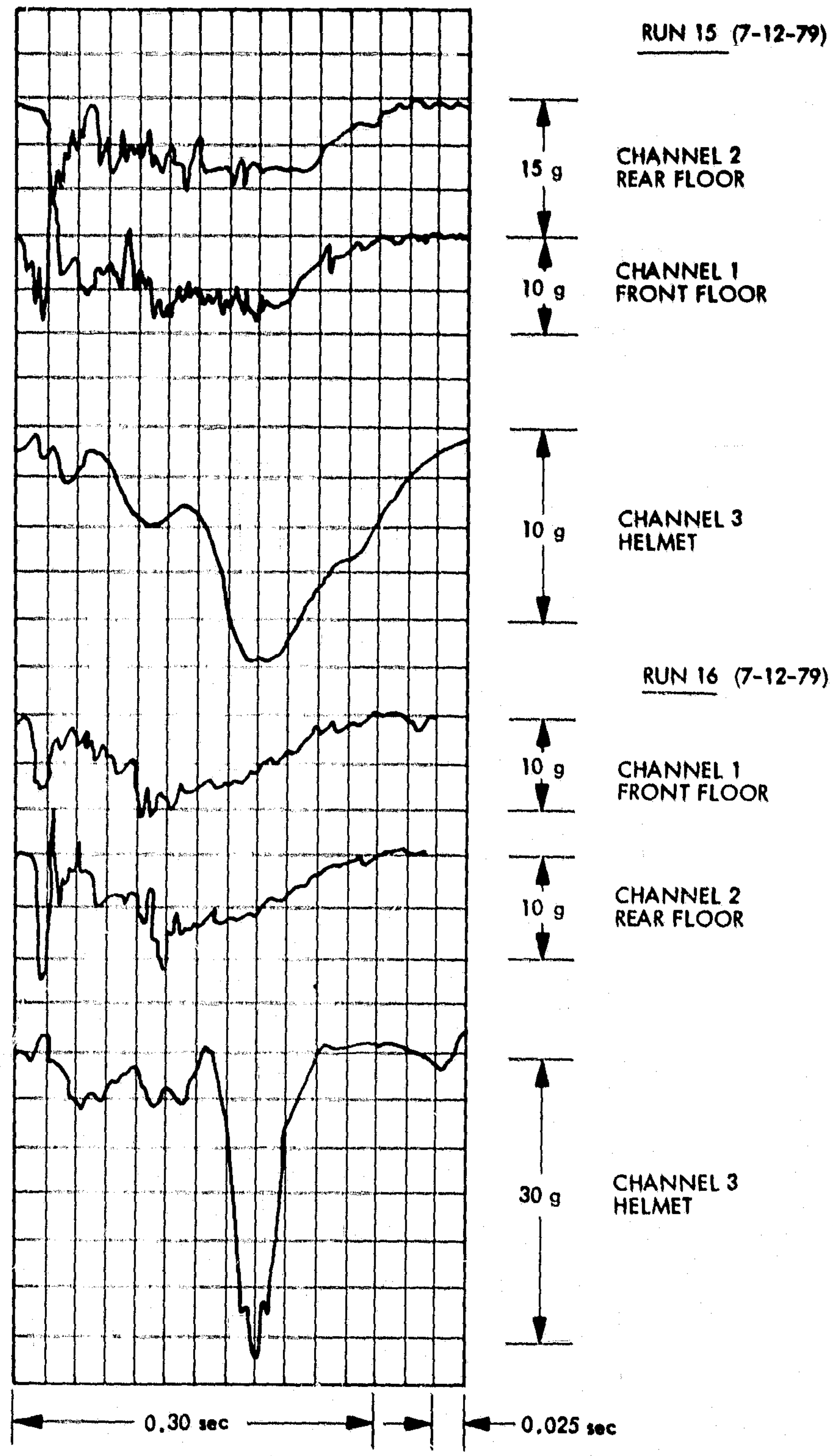

Figure 4-3. Accelerometer Traces; Run 15 and Run 16

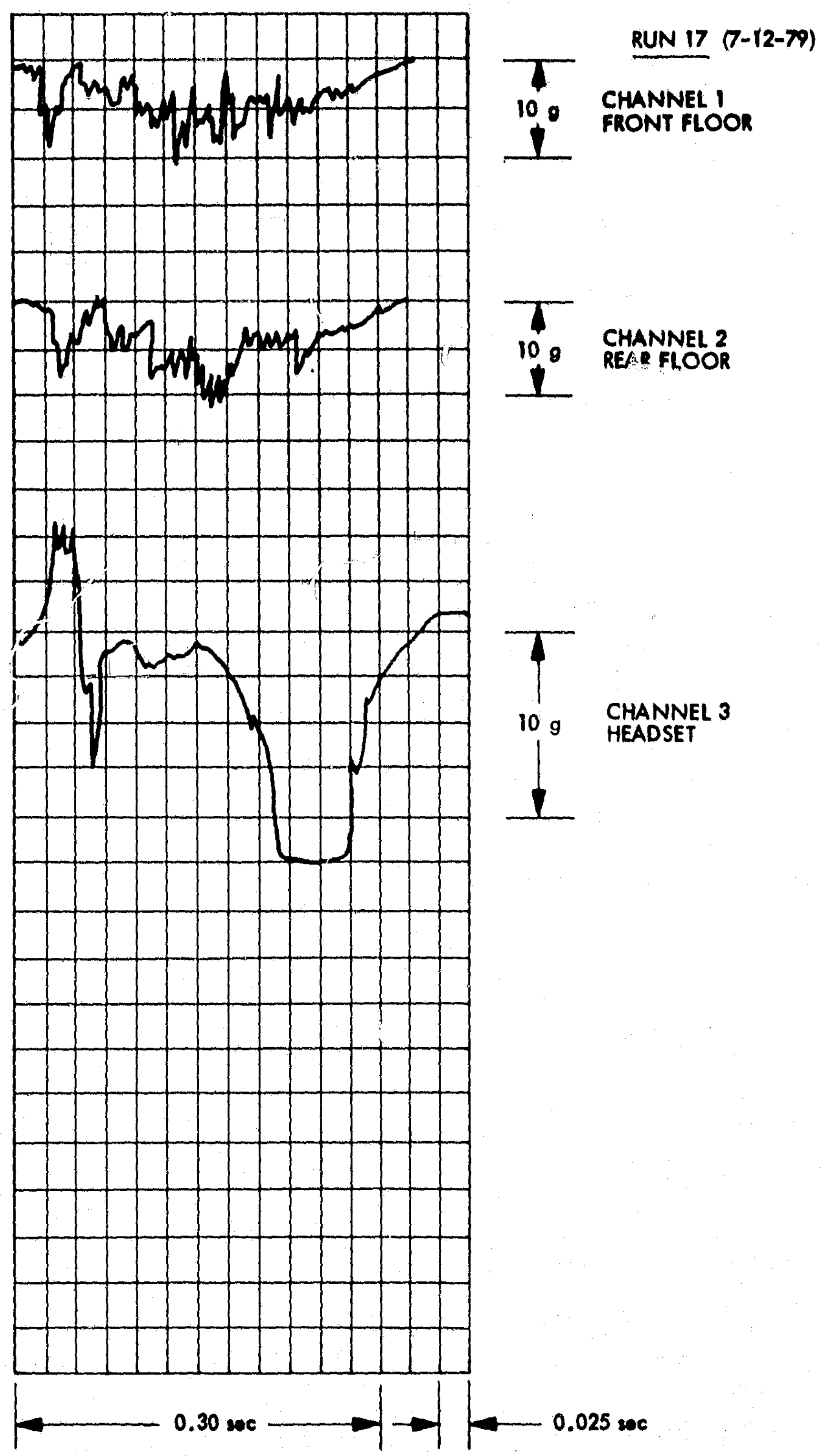

Figure 4-4. Accelerometer Traces; Run 17

Table 4-2. Accelerations

Date and Description	Test No.	Accel No.	Location	Peak (g)	Average 50 ms (g)	Average 100 ms (g)	Average 300 ms (g)	Notes
12/19/78 4500-lb car; 2-ft offset; 30 mph	13	1	Front	11.0	7.5	7.0	4.7	All tests used a Donner # 4130 Servo type accelerometer
		2	Back	10.0	7.5	7.1	4.9	
		3	Helmet	10+	12.0	10.5	5.0	
12/19/78 2250-lb car; axial; 30 mph	14	1	Front	9.5	7.0	6.1	4.9	
		2	Rear	12.5	6.5	6.1	4.4	
		3	Helmet	10+	9.5	8.5	5.5	
7/12/79 4500-lb car; axial; 30 mph	15	1	Front	9.5	7.5	6.7	4.8	
		2	Rear	10.0	6.5	6.1	4.6	
		3	Helmet	---	11.0	9.6	5.5	
7/12/79 4500-lb car; axial; 30 mph	16	1	Front	12.5	9.0	8.0	4.8	
		2	Rear	13.0	8.5	7.0	4.9	
		3	Helmet	32.0	21.0	12.5	5.8	Playback scale change
7/12/79 4500-lb car; 15° angle; 30 mph; 2-ft offset	17	1	Front	11.0	7.0	6.0	4.2	
		2	Rear	11.5	7.5	6.1	4.8	
		3	Helmet	12.5	12.0	9.5	5.5	Playback scale change

The predicted average acceleration is given by:

$$V = a\ t$$

where

$V = 44$ ft/sec

$t = 0.300$ sec

$$a = \frac{44}{0.30} = 147 \text{ ft/sec}^2 = 4.6 \text{ g}$$

This is consistent with optical and accelerometer data.

2. Driver

Accelerometer 3 was fastened to the driver's helmet with its axis horizontal when the driver's head was upright. However, at impact the driver's head rotated as shown in Figure 4-5, and the accelerometer measures acceleration along the arc of rotation.

To observe the deceleration traces due only to helmet rotation, a series of 64 laboratory tests was carried out. In most cases, the helmet was placed on an engineer who suddenly rotated his head forward until his chin hit his chest. Test 5H* was such a test. In other cases, the helmet was dropped on a foam pad that was on a table. Test 62H was such a test.

It was found that for Runs 13, 14, 15, and 17, the superposition of the Test 5H trace on that of the car frame resulted in an accelerometer trace that closely approximated the actual helmet acceleration trace (see Figures 4-6, 4-7, 4-8, and 4-9).

In Run 16, the helmet trace indicated a high acceleration for less than 50 ms. This was probably due to the impact of the helmet against the steering wheel.

*H signifies a test conducted in the laboratory on a helmet.

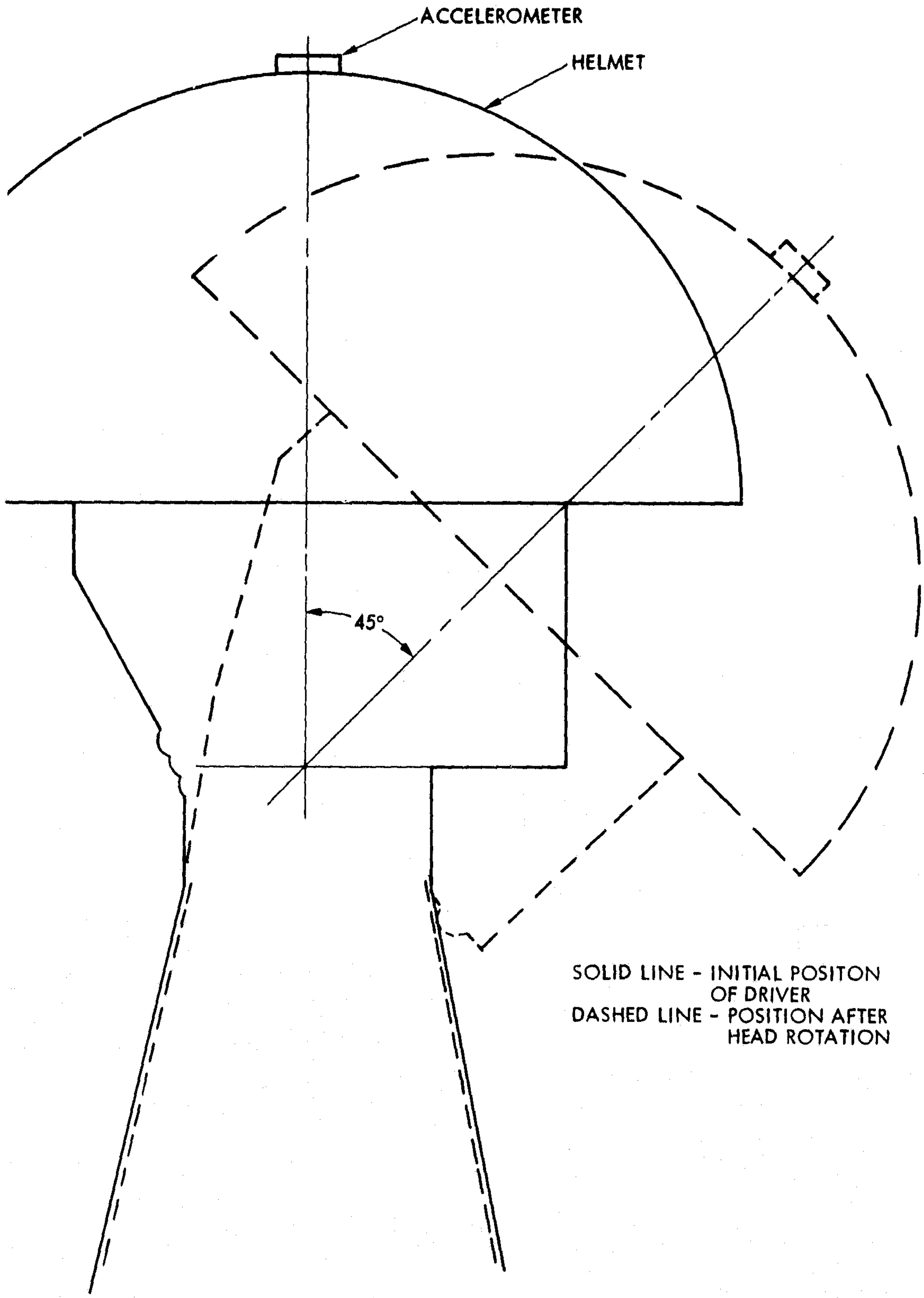

Figure 4-5. Rotation of Driver's Helmet (Side View)

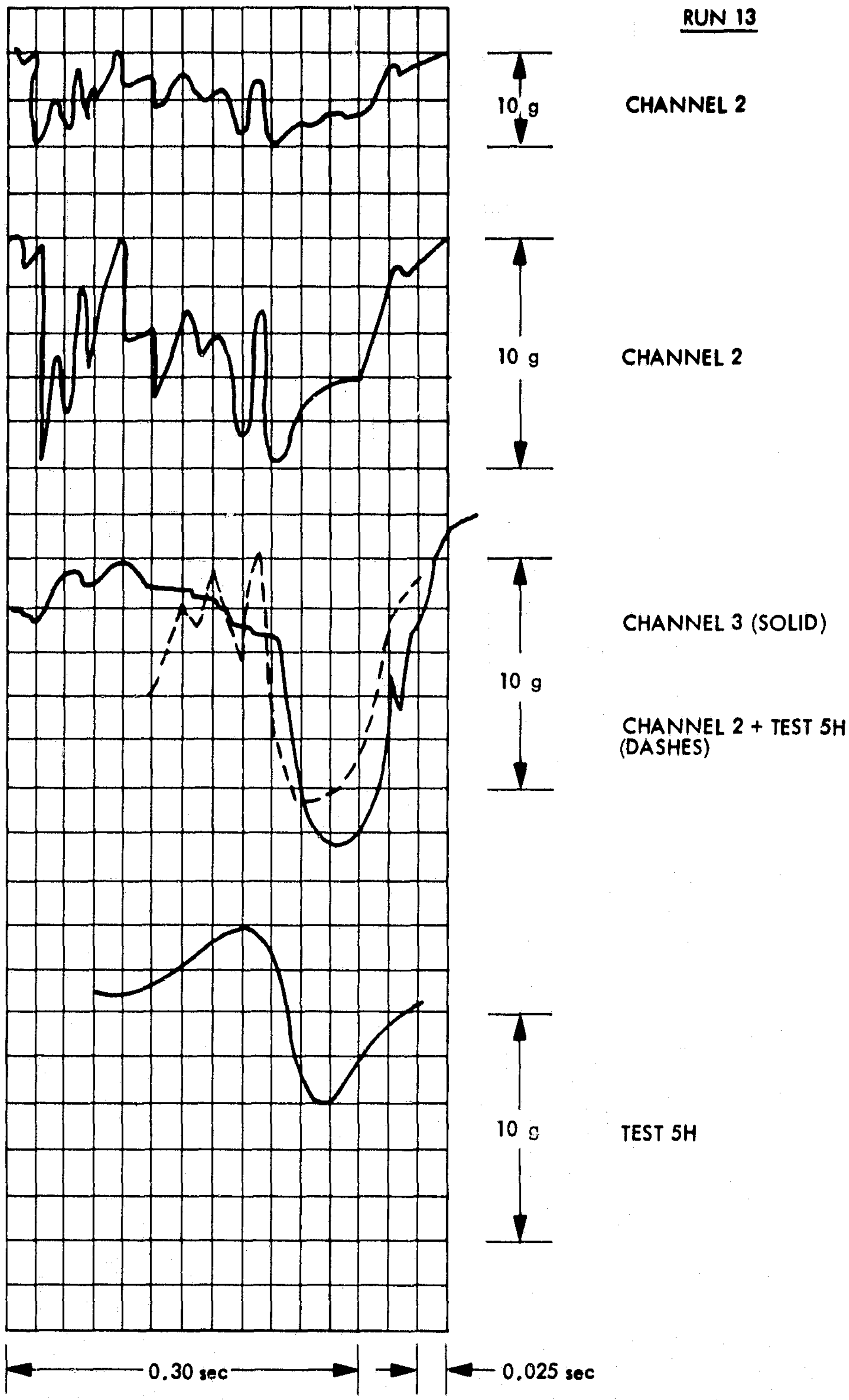

Figure 4-6. Combined Field and Laboratory Traces for Helmet; Run 13

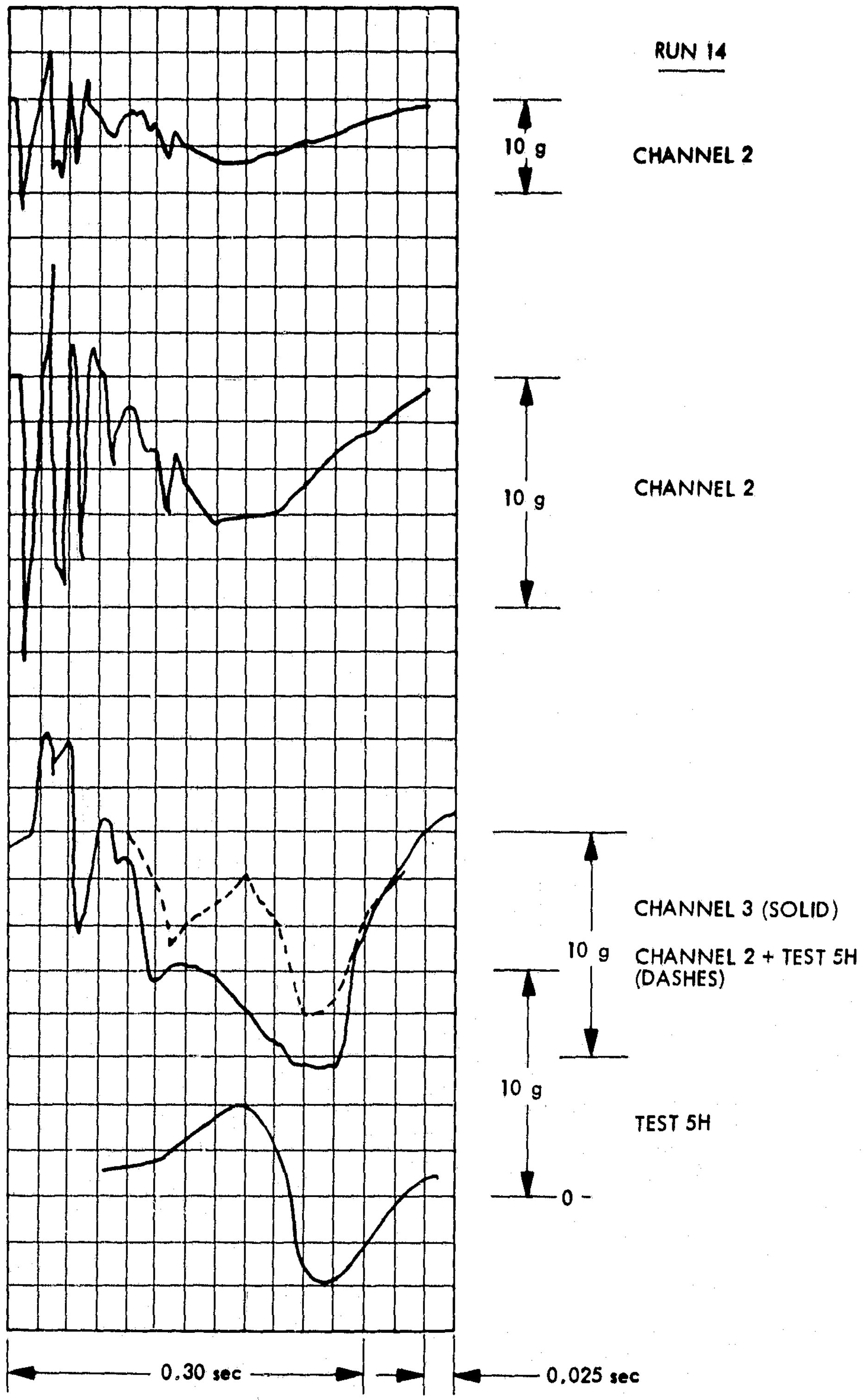

Figure 4-7. Combined Field and Laboratory Traces for Helmet; Run 14

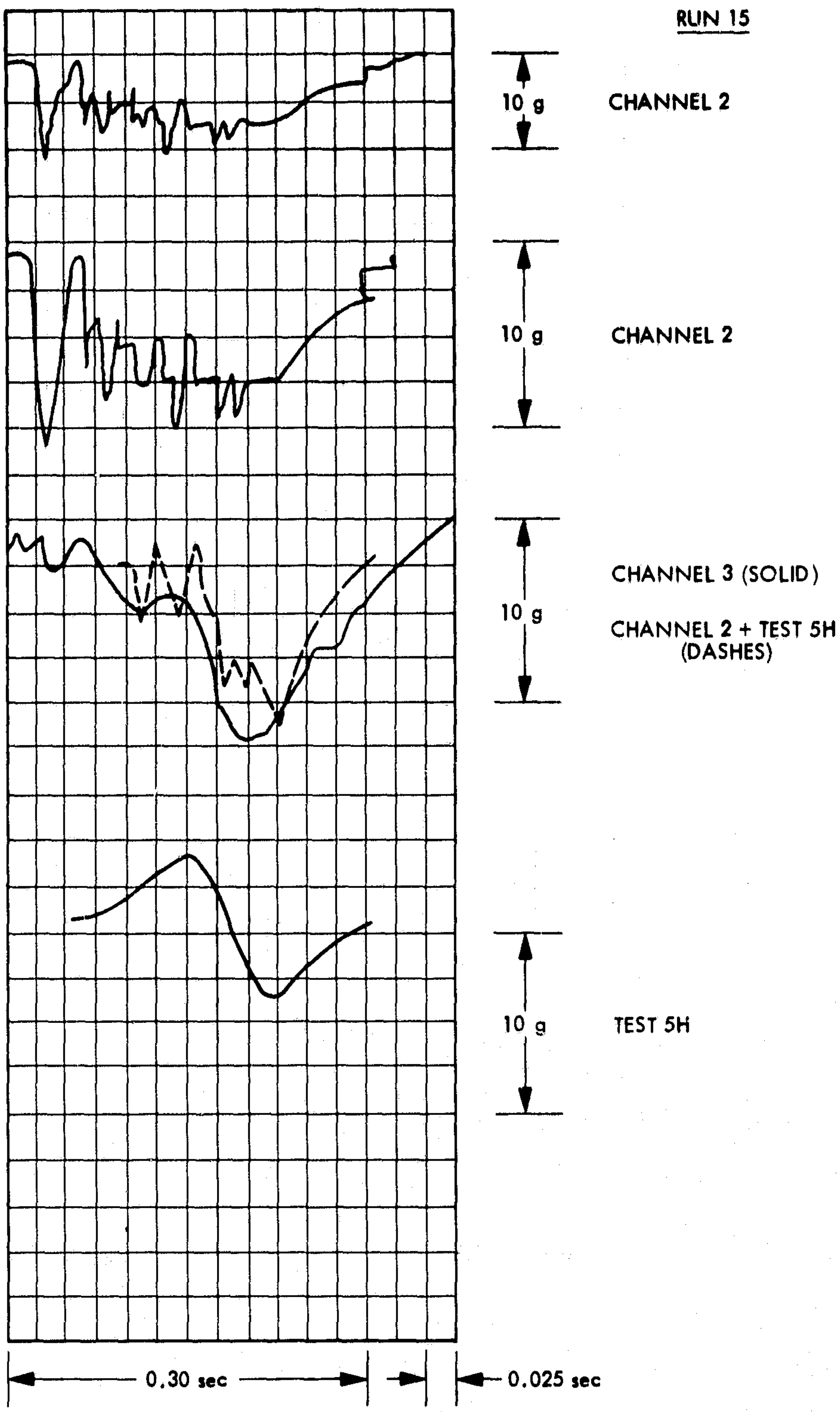

Figure 4-8. Combined Field and Laboratory Traces for Helmet; Run 15

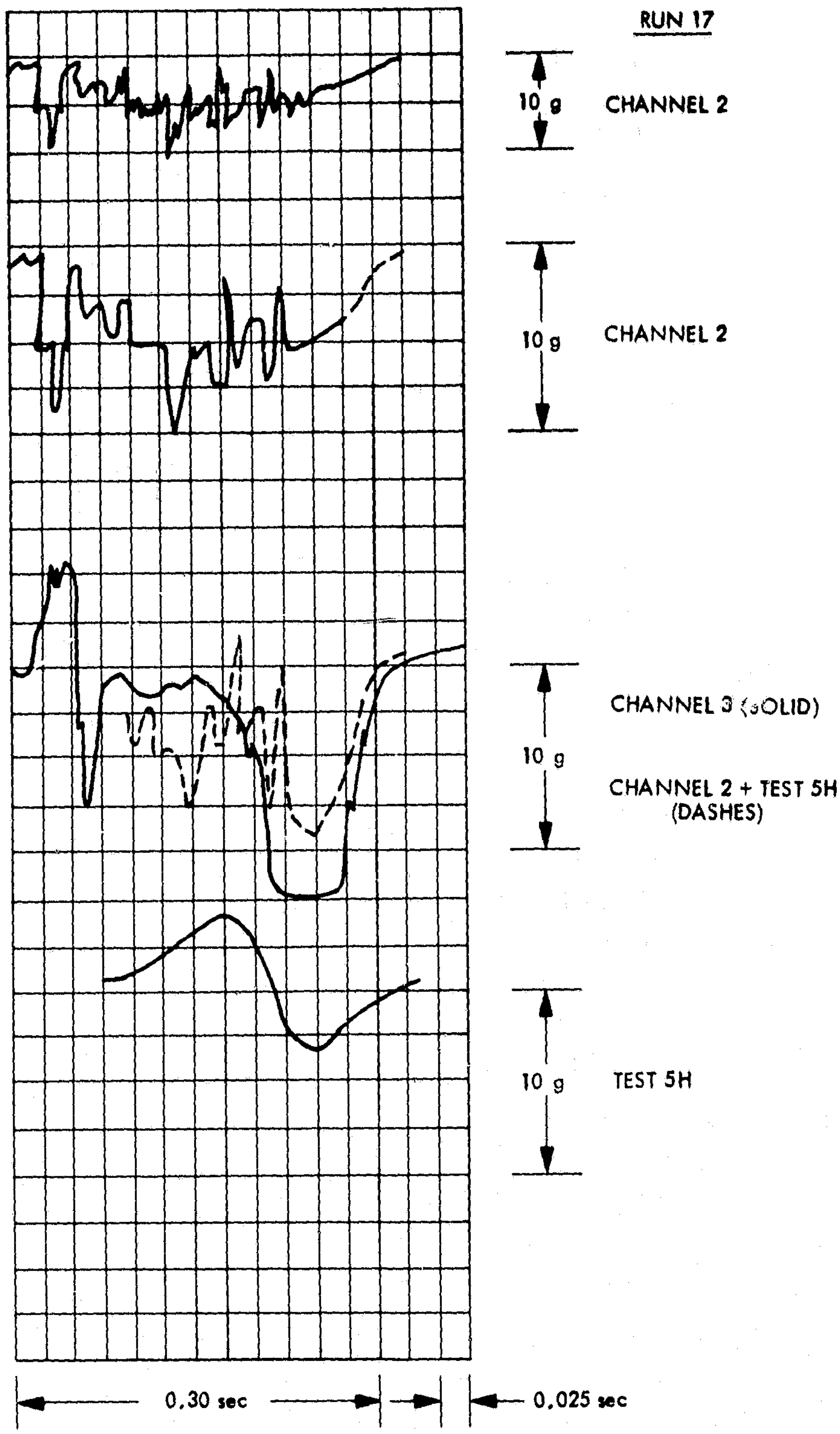

Figure 4-9. Combined Field and Laboratory Traces for Helmet; Run 17

The impact of the helmet against the steering wheel had been simulated by Test 62H. The superposition of Test 62H on the Channel 2 acceleration for Run 16 closely approximates the helmet accelerometer trace (see Figure 4-10).

It should be noted that Reference 3 does not require accelerometer measurements to be made on the driver. Since humans can safely withstand accelerations of 40 g for durations of less than 50 ms (see Figure 4-11), at no time was the driver in danger because of excessive accelerations.

The driver performed all impacts accurately. In no case did he experience more than a temporary discomfort. His comments appear in Table 4-3.

3. Instrumentation

To verify the accelerometer data, comparisons were made with the motion picutres through use of their timing marks (see Figure 4-12).

4. Barrier

Pictures of the barrier before and after impact appear in Figures 4-13 and 4-14.

B. ANALYSIS

Figure 4-15 shows the theoretical relationship of the average acceleration experienced in a crash versus the impact velocity for various compression distances. The compression distance includes that of both barrier and car deformation.

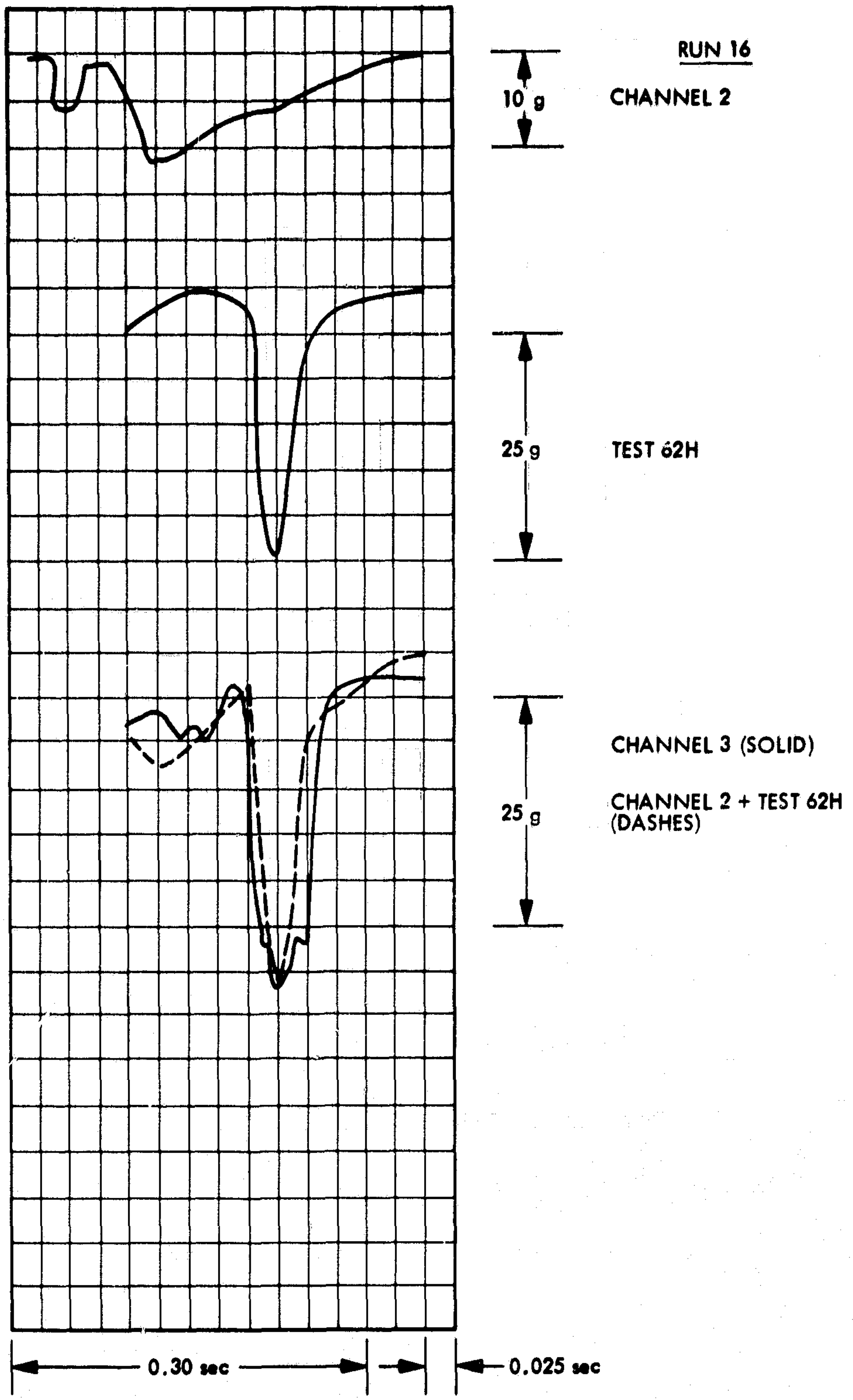

Figure 4-10. Superposition of Test 62H on Channel 2 for Run 16

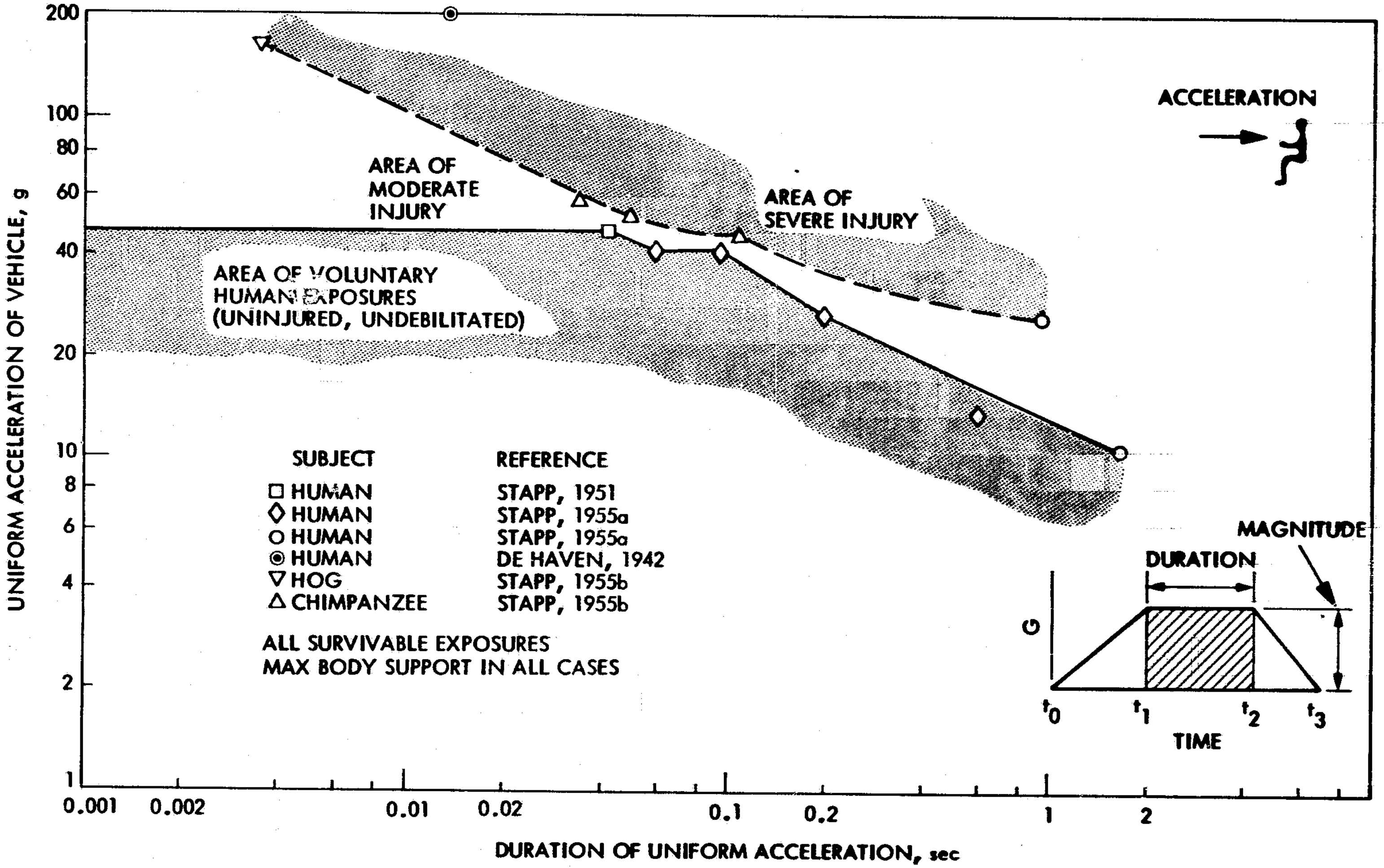

Figure 4-11. Effects of Acceleration on Live Subjects (From California Report 636405-2, October 1970, Ref. Caltrans (G. Sternumward) EIBAND, 1959)

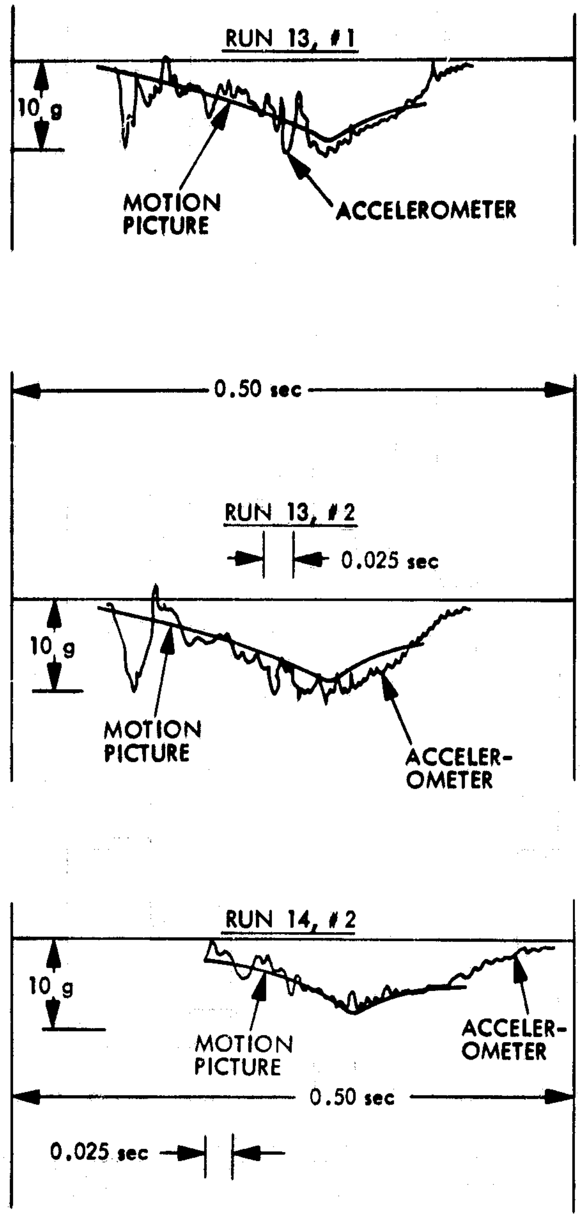

Figure 4-12. Deceleration Rates

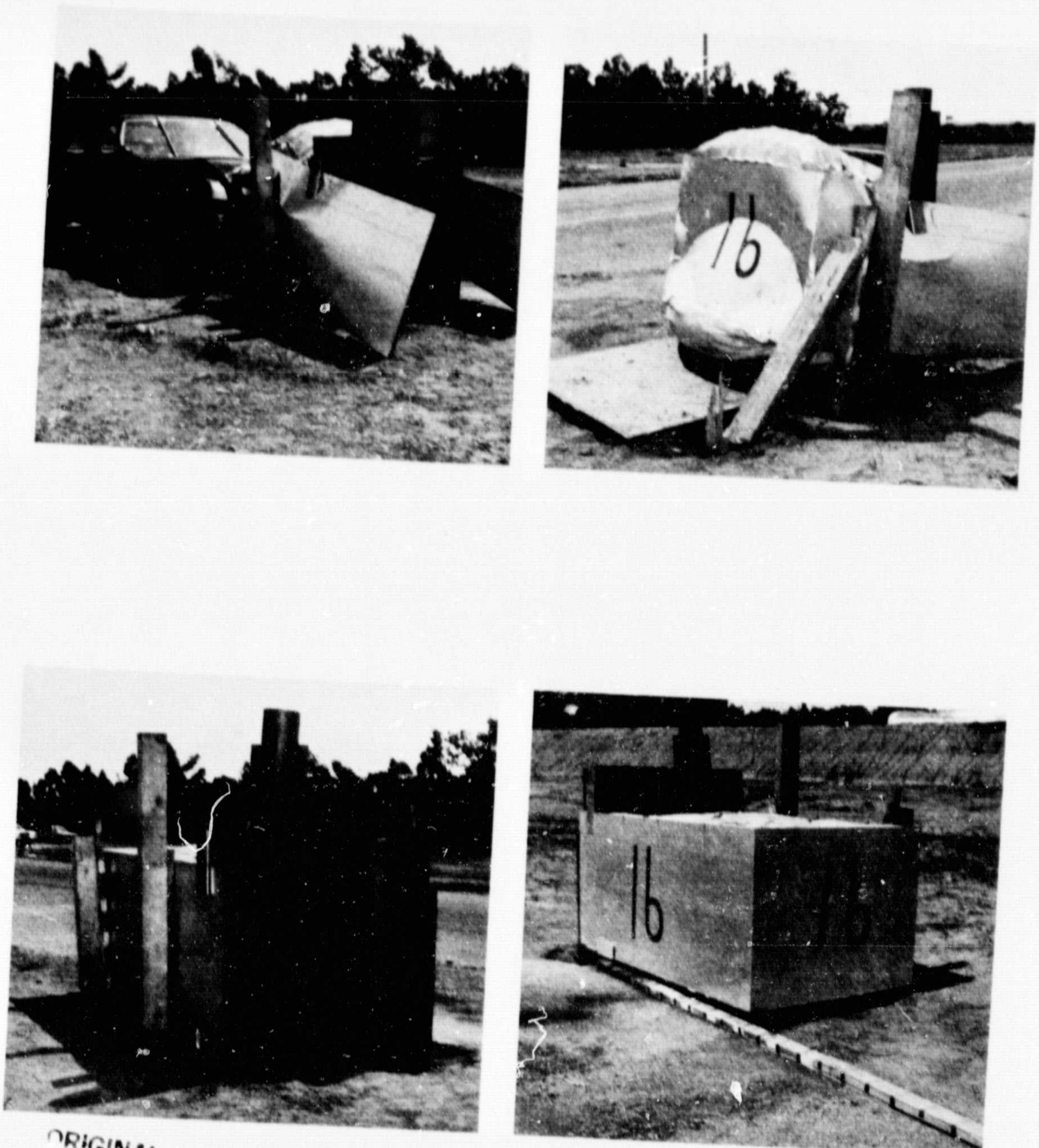

Figure 4-13. Test 16 Before and After Crash

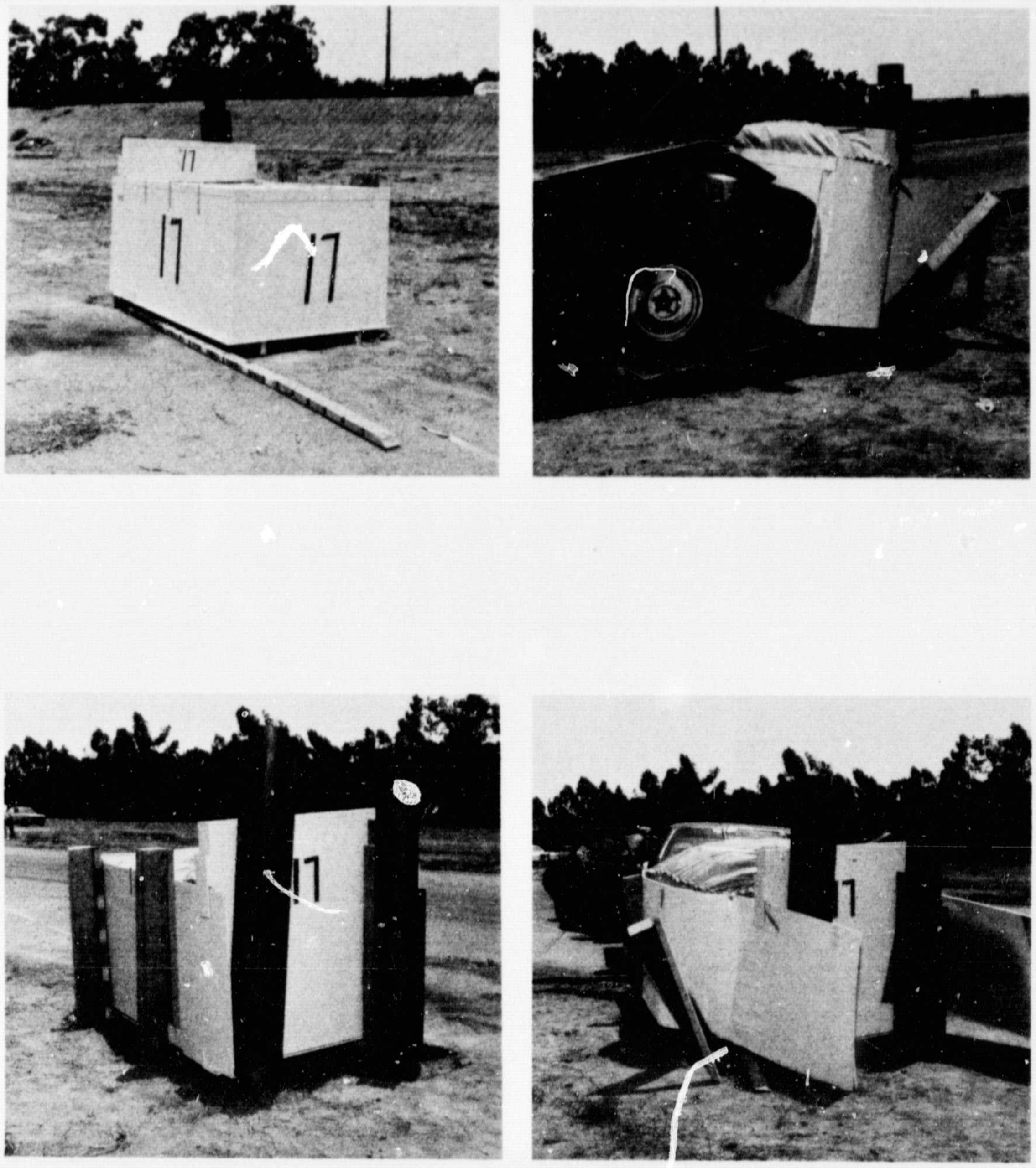

Figure 4-14. Test 17 Before and After Cras

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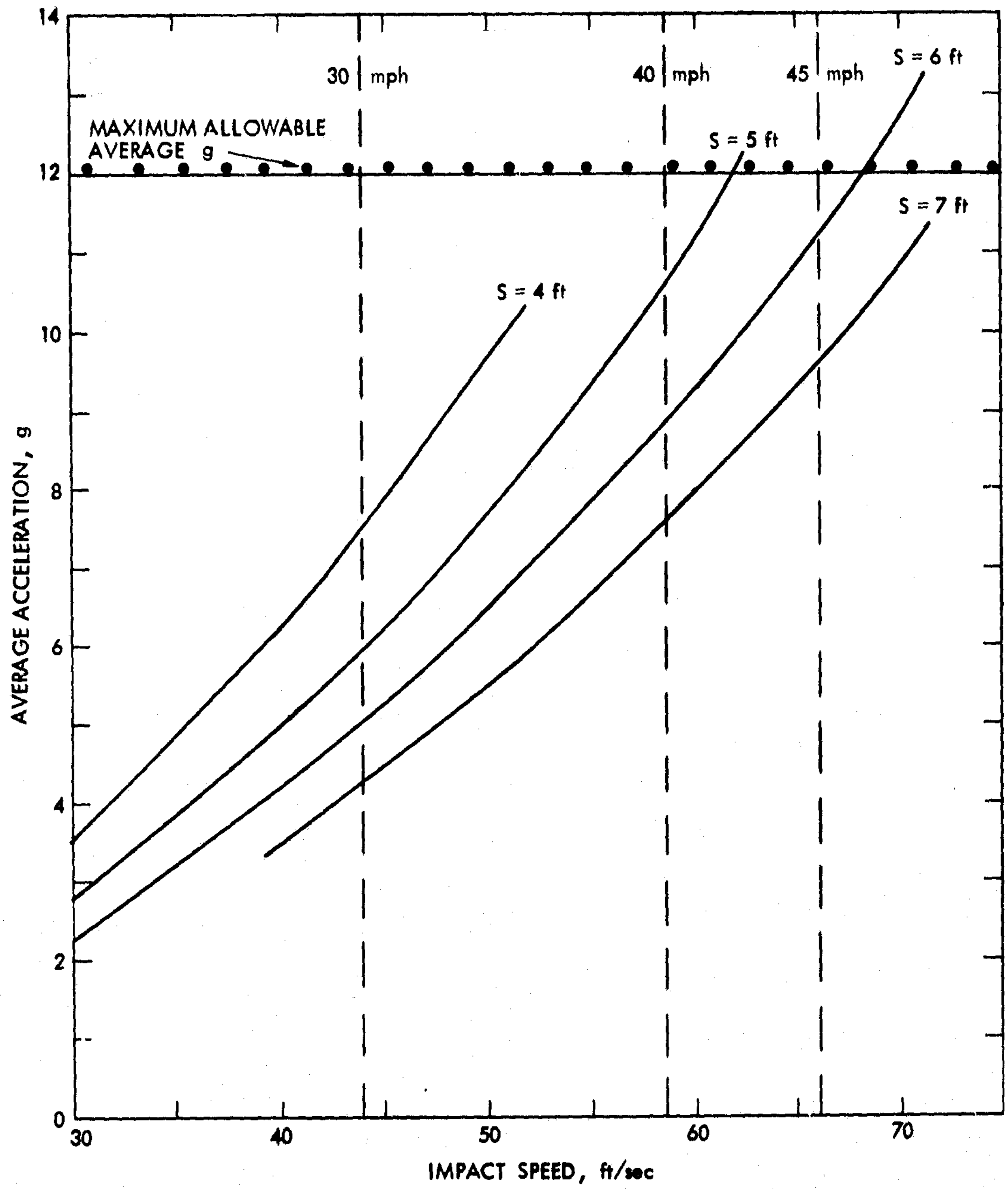

Figure 4-15. Average g vs Impact Speed

To illustrate, if the average acceleration for the first 250 ms were 9 g and for the last 50 ms were 20 g, the average deceleration would be 11 g. Referring again to Figure 4-11, the short term (50 ms) exposure to 20 g acceleration is not dangerous to a passenger with a shoulder harness restraint and the 11-g average deceleration is less than the 12 g that Reference 3 permits.

Since the car crashes never did utilize the full energy absorption capability of the JPL barriers, it is clear that these barriers would have provided for impacts above 30 mph that would satisfy the requirements of Reference 3. The following analysis is used to predict realistically what the situation would be for a 40-mph impact.

If the same force were to act for a 6-ft travel distance, the energy absorbed would be increased by 20% (6/5 - 120%). This corresponds to a velocity increase of 9.5% (1.20 = 1.095). The impact speed could then be about 33 mph (1.095 x 30 = 33).

From an energy absorption standpoint, the 4500-lb car traveling at 30 mph (44 ft/sec) has a kinetic energy of:

$$\frac{1}{2} M V^2 = \frac{1}{2} \times \frac{4500}{32.2} \times 44^2 = 135{,}000 \text{ ft-lb}$$

Assuming that the average force acts for the entire 5 ft of travel, the average force is 135,000/5 = 27,000 lb.

Tests on empty beverage cans show that as bottoming is approached, the average force increases non-linearly. Assuming that this non linear force increases by a factor of 4 for the additional travel, the energy absorbed by 108,000 ft-lb (5 x 27,000) to 243,000 ft-lb which is sufficient to permit a 40 mph crash. This would correspond to a 9-g acceleration for a 6-ft travel impact speed of 40 mph, as shown in Figure 4-15.

Table 4-3. Driver's Comments After Each Test

Test No.	Comment
9	That's a hard hit. A severe shock.
10	About the same as 9.
11	Not bad at all.
12	That time I knew I hit something solid.
13	Not too bad.
14	Not too bad.
15	I've been hit harder before. Not too bad but harder than 13 and 14.
16	Harder than the last one, (15) but not as bad as some earlier tests.
17	Harder than the last tests. My teeth bit my tongue. That has happened before in tests many times. Still not as hard as 9 or 10.

Based on Tests 13 through 17, the average deceleration over the 300 ms period was 4.6 g. This corresponds to a compression distance of 6 ft, which is about the observed combined deformation of car and barrier. Extrapolating the "S = 6 ft" curve to a 40-mph impact velocity curve, this would correspond to about 9.3 g -- a little above the 6-8 average g recommended in Reference 3, but well below the 12 g permitted. It should be noted that at higher speeds the excursion would increase until "bottoming" occurred. Considering both car and barrier deformation "S" at bottoming is probably in excess of 7 ft. Referring again to Figure 4-15, this would mean an average deceleration of about 9.7 g at 45 mph — also well below the 12 g permitted. There is a danger in extrapolating to high speeds in that a rapid increase in acceleration will occur once bottoming occurs. But even if this happens, the average acceleration may still be satisfactory.

Even at 45 mph, the average g level is less than the 12 g permitted in Reference 3. Reference 3 states "the preferred maximum vehicle acceleration average is 6-8 g and the maximum average permissible vehicle deceleration is 12 g as calculated from vehicle impact speed and passenger compartment stopping distance."

Based on the above, it seems reasonable to assume that the barrier is capable of protecting the occupants for vehicular impacts in excess of the 30 mph tested, and that 40 mph appears to be a reasonably safe crash speed with 45 mph the likely upper limit.

SECTION V

CONCLUSIONS

The JPL barrier described in this report meets the requirements of Reference 3 at 30 mph and probably would meet that requirements at 40-45 mph. The design is non-proprietary. The design goal of having a cost of less than $500 per installation still needs to be verified.

The basic JPL barrier design can be extended for higher speed applications, in cases such as gore protectors, where longer crushing distances are feasible.

The use of a live driver for the tests (as opposed to remote operation) provided confirmation that g loads were not excessive. The driver also verified that the shock he experienced in the 55-gal drum tests was greater than that of Tests 13 and 17 on the JPL design.

It should be noted that where space limitations preclude the use of a 6-ft long barrier, a stiffer, shorter barrier could be used without exceeding the 12-g average acceleration permitted in Reference 3 (see Figure 4-11).

REFERENCES

1. Decision Analysis of FCP (Federal Coordination Program) Project 1T; Advanced Vehicle Protection System, 1975.

2. Knoell, A. and Wilson, A., Modular Disposable Crash Cushion; A Concept Investigation, Technical Memorandum 33-795, Jet Propulsion Laboratory, Pasadena, California, August 15, 1976.

3. Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances, NCHRP Report 153 updated by Transportation Research Circular Number 191, Transportation Research Board, National Academy of Sciences, Washington, D.C., February 1978.

APPENDIX

SIGNIFICANCE OF PROBLEM OF CARS IMPACTING TREES AND POLES

The following data were provided by the Bureau of Accident Analysis, Pennsylvania Department of Transportation. Statistics are for the State of Pennsylvania during the period January — December 1976.

Table A-1 provides data on various fixed objects that were hit. The main causes of both major injuries and moderate injuries were trees and utility poles.

Table A-2 provides data on fatalities for various first objects hit. As might be expected, the largest number of deaths (556) resulted when automobiles were hit first. This was followed when pedestrians (346) and trucks were hit first. But closely behind were deaths resulting when trees (188) and poles (166) were the first objects hit.

Table A-3 provides a set of data on injuries that is in general agreement with the other tables.

Table A-4 provides data on accident description and severity of damage. The "hit fixed object" category is the type that caused the greatest number of fatalities and the most property damage, and was second in the number of injuries. Trees and utility poles are not the only fixed objects that are hazardous, but, as shown in Table A-1, these are the principal offenders in this category.

Table A-5 provides data on accident description vs severity of injury. Again the largest number of major injuries and the significant number of other injuries are clearly the result of hitting a fixed object.

Table A-1. Fixed Object Hit vs Severity of Injury*

Fixed Object Hit	Total Accidents by Injury Type				Total Injuries
	Major Injury	Moderate Injury	Minor Injury	Severity Unknown	
Parked Vehicle	2,027	1,351	1,399	875	5,652
Tree	3,156	1,474	1,052	128	5,810
Guard Rail	1,880	1,203	1,019	104	4,206
Median Barrier	375	265	238	13	891
Bridge Abutment	435	156	134	21	746
Utility or Light Pole	4,305	2,114	1,628	410	8,457
Permanent Traffic Signal	54	24	27	6	111
Permanent Traffic Sign	327	176	153	5	661
Curb	241	135	128	28	532
Temporary Traffic Control Device	39	21	29	6	95
Miscellaneous Object	1,969	1,117	983	208	4,277
Bridge Railing or Wall	300	166	157	23	646
Snow Bank	20	12	24	1	57
Embankment	1,825	1,133	883	77	3,918
Permanent Overhead Structure	27	32	19	1	79
Culvert	301	127	107	11	546
Total	17,281	9,506	7,980	1,917	36,684

*From Bureau of Accident Analysis, Pennsylvania Department of Transportation; "A Statistical Summary for the Period Jan through Dec 1976 Encompassing all Pennsylvania"

Table A-2. First Object Hit vs Age of Persons Killed*

First Object Hit	Number of Persons Killed Age Group										
	0-4	5-9	10-14	15-19	20-24	25-34	35-44	45-64	Over 64	Unknown	Total
Non-collision	3	0	1	21	23	20	7	7	1	0	83
Automobile	4	11	24	89	94	92	53	123	62	4	556
Truck	3	5	8	40	45	29	25	39	26	0	220
Bus	0	1	0	3	4	0	1	1	1	0	11
Motorcycle	0	1	0	6	11	7	3	2	0	0	30
Bicycle	1	2	7	0	1	0	1	0	0	0	12
Pedestrian	23	41	24	14	20	21	25	71	106	1	346
Farm Equipment	0	0	0	1	0	0	1	0	0	0	2
Horse and Buggy	0	0	0	0	0	1	0	1	1	0	3
Train	0	0	0	4	3	4	2	7	3	0	23
Ambulance	0	0	0	0	0	0	0	0	1	0	1
Deer	0	0	0	0	1	0	0	1	0	0	2
Trailer or Mobile Home	0	0	0	0	0	1	0	1	0	0	2
Parked Vehicle	0	0	0	6	7	10	4	9	11	1	48
Tree	0	0	3	49	48	38	12	22	16	0	188
Guard Rail	0	1	1	19	23	20	12	18	2	0	96
Median Barrier	0	0	0	2	2	3	2	3	0	0	11
Bridge Abutment	1	0	0	7	15	16	7	6	3	0	55
Utility or Light Pole	2	0	0	55	37	26	10	25	9	2	166
Permanent Traffic Signal	0	0	0	1	1	1	0	0	0	0	3
Permanent Traffic Sign	0	0	0	1	2	2	1	2	0	0	8
Curb	0	0	0	0	1	0	0	0	0	0	1
Temporary Traffic Control Device	0	0	0	0	0	1	0	1	0	0	2
Miscellaneous Object	0	0	1	13	22	17	6	13	8	0	80
Bridge Railing or Wall	0	0	0	0	1	1	1	1	0	0	4
Embankment	2	0	1	12	12	14	4	5	2	0	52
Permanent Overhead Structure	0	0	0	0	0	0	0	1	0	0	1
Culvert	0	0	1	6	3	4	2	1	2	0	19
Total	39	62	71	349	376	327	179	360	254	8	2,025

*From Bureau of Accident Analysis, Pennsylvania Department of Transportation; "A Statistical Summary for the Period Jan through Dec 1976 Encompassing all Pennsylvania"

Table A-3. First Object Hit vs Age of Person Injured*

First Object Hit	Number of Persons Injured - Age Group										
	0-4	5-9	10-14	15-19	20-24	25-34	35-44	45-64	Over 64	Un-known	Total
Non-collision	80	72	159	1,370	1,204	1,005	388	437	89	97	4,901
Automobile	2,163	2,562	2,993	12,821	12,389	13,687	7,833	14,419	4,541	2,728	76,136
Truck	177	198	300	1,128	1,157	1,461	836	1,279	337	176	7,049
Bus	10	66	62	119	66	112	67	106	33	248	889
Motorcycle	5	17	64	474	532	372	99	81	11	45	1,700
Bicycle	18	177	306	215	101	46	15	17	3	69	967
Pedestrian	463	1,377	787	561	384	434	247	612	498	602	5,965
Animal - Other than Deer	1	1	4	39	31	40	19	18	7	3	163
Farm Equipment	9	1	5	14	16	20	8	16	8	2	99
Horse and Buggy	3	6	11	6	3	21	3	11	6	5	75
Train	2	4	4	11	14	20	10	23	2	2	92
Other	3	11	8	15	19	15	4	13	3	6	97
Ambulance	1	0	0	4	6	8	7	4	1	5	36
Firetruck	0	0	1	3	10	2	3	6	2	3	30
Other Emergency Equipment	1	0	1	9	20	59	25	12	5	5	137
Deer	4	3	6	38	44	43	22	34	11	4	209
Trailer or Mobile Home	1	0	1	11	20	12	14	16	3	1	79
Parked Vehicle	88	88	156	1,178	1,074	957	463	674	261	713	5,652
Tree	70	70	203	2,127	1,303	919	385	510	129	94	5,810
Guard Rail	62	74	100	946	987	907	398	524	128	80	4,206
Median Barrier	11	9	15	161	196	198	87	171	34	9	891
Bridge Abutment	8	8	24	254	156	135	61	75	17	8	746
Utility or Light Pole	100	118	206	2,679	2,007	1,538	616	809	192	192	8,457
Permanent Traffic Signal	1	0	2	27	25	25	10	9	7	5	111
Permanent Traffic Sign	11	9	12	179	184	108	53	72	27	6	661
Curb	12	4	10	125	136	111	44	54	17	19	532
Temporary Traffic Control Device	0	0	5	7	27	28	7	14	4	3	95
Miscellaneous Object	53	57	95	1,215	973	796	331	462	149	146	4,277
Bridge Railing or Wall	12	15	18	144	148	138	71	69	16	15	646
Snow Bank	3	2	7	9	5	17	7	7	0	0	57
Embankment	62	60	107	1,149	918	716	332	437	97	40	3,918
Permanent Overhead Structure	0	2	3	13	16	13	11	16	1	4	79
Culvert	4	10	19	169	122	102	53	50	13	4	546
Totals	3,438	5,021	5,694	27,220	24,293	24,065	12,529	21,057	6,652	5,339	135,308

*From Bureau of Accident Analysis, Pennsylvania Department of Transportation; "A Statistical Summary for the Period Jan through Dec 1976 Encompassing all Pennsylvania"

Table A-4. Accident Description vs Severity of Accident*

	Total Accidents by Type					
Accident Description	Fatal	Injury	Property Damage	Total Accidents	Total Fatalities	Total Injuries
Head-on	250	1,406	1,311	2,967	325	3,434
Rear-end	48	17,002	39,010	56,060	53	26,984
Angle	362	32,231	89,477	122,070	423	53,640
Sideswipe	40	1,532	7,360	8,932	53	2,465
Backing Up Accident	5	617	6,277	6,899	6	859
Hit Pedestrian	340	5,519	210	6,069	345	5,930
Hit Fixed Object	650	26,879	62,542	90,079	734	36,511
Non-collision	83	3,611	3,439	7,133	83	4,871
All Others or Unknown	3	486	3,076	3,565	3	614
Total	1,789	89,283	212,702	303,774	2,025	135,308

*From Bureau of Accident Analysis, Pennsylvania Department of Transportation; "A Statistical Summary for the Period Jan through Dec 1976 Encompassing all Pennsylvania"

Table A-5. Accident Description vs Severity of Transportation*

Accident Description	Total Accidents by Injury Type				Total Injuries
	Major Injury	Moderate Injury	Minor Injury	Severity Unknown	
Head-on	1,802	791	723	118	3,434
Rear-end	4,816	4,778	16,054	1,336	26,984
Angle	17,108	13,594	20,385	2,553	53,640
Sideswipe	803	643	878	141	2,465
Backing Up Accident	152	211	434	62	859
Hit Pedestrian	1,806	841	1,931	1,352	5,930
Hit Fixed Object	17,216	9,435	7,945	1,915	36,511
Non-collision	2,196	1,445	1,083	147	4,871
All Others or Unknown	234	173	183	24	614
Total	46,133	31,911	49,616	7,648	135,308

*From Bureau of Accident Analysis, Pennsylvania Departme of Transportation; "A Statistical Summary for the Period Jan through Dec 1976 Encompassing all Pennsylvania"